The potential of Russia to increase its wheat production through cropland expansion and intensification

Dissertation

Zur Erlangung des akademischen Grades doctor rerum naturalium
(Dr. rer. nat.)

im Fach Geographie

eingereicht an der
Mathematisch-Naturwissenschaftlichen Fakultät
der Humboldt Universität zu Berlin
von
Dipl. Geogr. Florian Schierhorn

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Tag der mündlichen Prüfung: 07.09.2015

Acknowledgments

I am really happy and thankful to have been working in such a pleasant and supportive working environment at IAMO created not only by the scientists but also the administrative staff. In addition to this thesis, I have received so much support during the exciting and sometimes challenging years I spent here. I would like to take the opportunity here to express my greatest and deepest gratitude to a few people:

First and foremost, I like to thank *Daniel Müller* for his countless and outstanding scientific and non-scientific advice. *Daniel*, I am deeply grateful for being supervised by you; I have benefited so much from your ideas, inspiration, knowledge, and your commitment to science. You gave me freedom to pursue my research, *Daniel* and navigated me well through challenging times and taught me that a rejected paper is not the end of the world – it is just about staying focused and improving it to get it the next time. You really encouraged me.

I have also been truly privileged to have *Alfons Balmann* as a supervisor and head of our department. First, *Alfons*, you made this unique research environment at the Land System Change Group of your department possible and you supported us in every possible way in order to establish research as the highest priority. Second, I deeply thank you for your feedback on our manuscripts, for valuable and inspiring discussions – often thematically far beyond geography – and for being available as a referee for this thesis.

Tobias Kümmerle, for valuable comments, fruitful discussions, and for being available as a referee for this thesis. I also would like to acknowledge your ongoing great support to young scientists and your integrative approach in initializing and conducting research projects.

Nicolas Vuichard, I thank you for providing me the opportunity to spend time at LSCE in Gif-sur-Yvette, for helpful discussions related to carbon sequestration due to land abandonment, and for refereeing this thesis.

Alexander Prishchepov, I thank you for endless and fruitful discussions on various topics related to the former Soviet Union countries and for all the valuable comments on our manuscripts.

Tim Beringer, for your great modelling support and for your feedback on my first manuscript.

Monireh Faramarzi, for visiting us two times in Halle to teach me the first steps in the SWAT model. I enjoyed this time so much! Moreover, I am grateful, *Monireh*, for your outstanding support in reviewing my manuscripts.

Sergiy Tkalych, for your great support during our adventurous and fun field trip and for friendship.

Friedrich Koch, for fruitful discussions, much appreciated modeling tips, mutual support, and for creating a very nice working environment in our office.

I thank our student collaborators *Jay, Guo, Tatjana, Natalie,* and *Silvia* for interpreting the Google Earth imagery and for their support in compiling the data.

I thank my LSC-colleagues and friends *Jerry, Friedrich, Daniel, Brett, Sasha, Kristin, Jens, Fang, Shemei, Roland,* and everybody else in our department for inspiration and a fun working environment.

I thank the IAMO-administration, particularly *Angela Scholz, Antje Barth, Heike Lehman, Sabine Tretin,* the IAMO-IT-crew, the IAMO-PR-crew, and many more for continuing selfless support to the scientists.

I thank *Martin Volk, Michael Strauch,* and *Felix Witting* for important support on SWAT-modeling.

I thank *Irina Kurganova* for valuable scientific discussions and for inviting me to Puschino.

I thank *Robert Müller and Stefan Erasmi* for important support during my times at the University of Gottingen and for paving my way to science.

Last, but of course not least, I thank friends and family: The biggest thanks is to my dearest *Jana* because your love and ample care helped me so much during the last years; the time with you made my life a lot more fun! Very special thanks to *Klodi, Marek, Christian, Aaron, Jonas, Adrian, Ihtiyor, Friedrich, Brett, Jerry, Taras, Konstantin,* and *Wiebke.* We have really come long way and I would like to thank you all for your personal support and friendship.

I thank my family for their love, care, and trust, and for being always supportive. *Christoph, Christiane, Karen, Joachim, Annemarie, Günther,* and *Elisabeth*, to you this thesis is dedicated!

Abstract

To meet the rapidly increasing food demand, food production must grow substantially while, at the same time, agriculture's impact on the environment must be reduced. Therefore, it is imperative to identify agriculturally underperforming regions, identify potential for land expansion and land intensification, and assess environmental tradeoffs for increasing food production. The primary objective of this dissertation is to systematically quantify untapped agricultural potentials in European Russia, where widespread abandoned agricultural lands and large yield gaps co-exist. We developed a spatial allocation model to produce annual cropland and cropland abandonment maps. Feeding the new maps into a dynamic vegetation model revealed that 470 Tg of carbon was sequestered in soil and vegetation due to the abandonment of 31 million hectares of cropland. Thus, the environmental consequences limit the potential for cropland expansion to abandoned cropland. We then calibrated a crop growth model for provincial wheat yields in European Russia and found average yield gaps of 1.51–2.10 t ha^{-1} under rainfed conditions and 3.14–3.30 t ha^{-1} under irrigated conditions. The cropland abandonment maps, spatial information on carbon sequestration due to cropland abandonment, and the estimates of yield gaps allowed us to estimate the potential of European Russia to increase its wheat production and to account for the carbon tradeoffs of cropland expansion. We demonstrated that European Russia can substantially increase its wheat production (up to 32 Mt under rainfed conditions). This increase is despite a limited expansion of wheat cultivation to reduce the trade-off from the high carbon emissions in re-cultivating older, abandoned cropland where most carbon is stored. Therefore, intensification of the existing croplands is recommended to be the major opportunity for future growth in agricultural production. This dissertation can help policy makers and agribusiness identify areas suitable for cropland expansion and better target agricultural inputs and infrastructures. Moreover, this dissertation contributes to better identifying and balancing trade-offs between environmental impacts and increasing agricultural production in European Russia.

Zusammenfassung

Angesichts des rasant steigenden Nahrungsmittelbedarfes steht die globale Landwirtschaft vor der großen Herausforderung, die Agrarproduktion massiv, aber umweltverträglich, zu steigern. Die Berechnung von regionalen Agrarpotenzialen, nicht zuletzt hinsichtlich der Umweltkosten der möglichen Produktionssteigerungen, ist daher von großer Dringlichkeit. Die vorrangige Zielstellung dieser Dissertation war die Berechnung nicht erschlossener landwirtschaftlicher Potenziale des Europäischen Russlands, wo riesige Brachflächen liegen und Agrarflächen häufig große Ertragslücken aufweisen. Wir haben ein räumliches Allokationsmodell entwickelt, dass die jährlichen Acker- und Ackerbrachflächen von 1991 bis 2009 kartiert. Diese Daten haben wir anschließend in ein dynamisches Vegetationsmodell integriert und damit berechnet, dass während der postsowjetischen Aufgabe von 31 Millionen Hektar Ackerland bis 2009 470 TgC in Boden und Vegetation gebunden wurden. Anschließend haben wir ein Pflanzenwachstumsmodell auf regionale Weizenerträge kalibriert und darauf basierend durchschnittliche Ertragslücken von 1.51-2.10 t ha^{-1} für natürliche (unbewässerte) und 3.14-3.30 t ha^{-1} für bewässerte Anbaubedingungen ermittelt. Die Karte der Ackerbrachflächen, räumlich-explizite Informationen über die Kohlenstoffspeicherung in Boden und Vegetation infolge der Ackerflächenaufgabe sowie unsere Ergebnisse der Ertragslückenberechnung haben wir zur Berechnung von Weizenproduktionspotenzialen verwendet. Unsere Ergebnisse zeigen, dass das Europäische Russland erhebliche Potenziale mobilisieren kann – bis zu 32 Millionen Tonnen für künstlich unbewässerte Bedingungen – obwohl ausschließlich jüngere Ackerbrachen zur Rekultivierung in unserem Modell berücksichtigt wurden. Ältere Brachflächen haben häufig große Mengen Kohlenstoff in Boden und Vegetation gespeichert; die Rekultivierung ältere Brachflächen würde zu hohen Emissionen führen. Eine wesentliche Schlussfolgerung dieser Dissertation ist daher, dass Produktionssteigerungen vorrangig durch Flächenintensivierung der bestehenden Ackerflächen erzielt werden sollten. Allerdings können die Ergebnisse dieser Arbeit helfen, Brachen für die Rekultivierung zu bestimmen, deren Rekultivierung relativ geringe Kohlenstoffemissionen nach sich ziehten. Zudem können die Ergebnisse dieser Arbeit nützlich sein, landwirtschaftliche Produktionsmittel effizienter einzusetzen und die Agrarproduktion besser auf die volatilen Klimabedingungen im Europäischen Russland einzustellen. Darüber hinaus trägt diese Arbeit dazu bei, bessere Abwägungen zwischen der Steigerung der Agrarproduktion einerseits und der Umweltverträglichkeit andererseits zu treffen.

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Chapter I Introduction

Environmental transformation during the Anthropocene

Approximately 160,000 years ago, modern humans, *Homo sapiens,* spread from Africa over virtually the entire land surface of the planet. However, approximately 10,000 years ago, the world population was a mere 5 million people, and population densities were very low. The agricultural 'revolution', which began approximately 10,000 years before present, allowed an expansion of the world population to 0.5 billion by AD 1650. Since that time, the population increased exponentially to more than 7.2 billion at present, mainly triggered by agricultural, medical, and industrial breakthrough developments (Goudie 2013). The last centuries are increasingly referred to as the *Anthropocene* epoch because the population boom and the associated pervasive impact of humans on the Earth's ecosystems (Crutzen 2006; Ellis et al. 2010; Steffen et al. 2007).

During the Anthropocene, the humans has dramatically changed the surface of the planet. From 1700 to 2000, land for agriculture and settlements increased from 5% to 39% of the Earth's terrestrial surface (Ellis et al. 2010). Agriculture, specifically has replaced 70% of the grassland, 50% of the savanna, 45% of the temperate deciduous biome, and large shares of the tropical forest biome (27%, Foley et al. 2011). The 20th century was the 'most dynamic period of anthropogenic ecosystem transformation of the past 300 years' and 'the terrestrial biosphere transitioned from a primarily wild and semi-natural state to a primarily used state' (Ellis et al. 2010). Today, croplands cover 1.53 billion hectares or 12% of the Earth's terrestrial surface and pastures cover 3.38 billion hectares or 26% of the Earth's terrestrial surface (Foley et al. 2011).

Agricultural land expansion contributed to loss of biodiversity and diminished soil health through loss of soil carbon, organic matter and nutrients. Agriculture has also triggered significant greenhouse gas emissions and has jeopardized many other ecosystem services (Foley et al. 2005; Houghton et al. 2012). The widespread agricultural land expansion in the tropics has been particularly worrisome because of the rich reservoirs of biodiversity and important ecosystem services (DeFries et al. 2002; Laurance 2007). Moreover, the tropics typically support relatively low agricultural yields and food benefits (Foley et al. 2011).

However, between 1961 and 2005, global cropland expanded by 27%, whereas crop production rose by 162%. Therefore, yield increases from land intensification have been the major driver for the large growth in food production (Burney et al. 2010). A 5-fold increase in fertilizer use and a 2-fold increase in irrigation, in parallel with the introduction of new crop varieties, livestock breeds, mechanization, and chemical weed control, led to a crop yield increase of 135%. (Burney et al. 2010; Foley et al. 2011). Yield increases resulting from the 'green revolution' saved substantial greenhouse gas emissions because it spared forests and shrublands from conversion to cropland (Borlaug 1983; Burney et al. 2010) and contributed to decreasing hunger during the second half of the twentieth century (FAO 2014).

Nevertheless, global agriculture production accounts for 25-35% of all greenhouse gases, pollutes aquatic ecosystems, is responsible for soil degradation (Pretty and Bharucha 2014), and is a major threat to species (Butchart et al. 2010; Díaz et al. 2006). Global agriculture is the major force driving climate change and the loss of various ecosystem services, pushing the environment beyond the 'planetary boundaries' (Rockstrom et al. 2009). On the other hand, billions of people derive their livelihoods from agriculture and, of course, agriculture feeds (most of) the world's population.

Despite the depletion of the Earth's resources, hunger and malnutrition still prevail and are the major causes of human death. One in eight of the world's population (800 million people) is currently undernourished, and 2 billion people suffer from various types of micronutrient malnutrition, i.e., hidden hunger that affects the health of women and children and is often overlooked (Hoddinott et al. 2012; Miller and Welch 2013). Hunger and malnutrition are commonly caused by poverty and many other socioeconomic factors (Misselhorn 2005; Müller and Krawinkel 2005), as well as short-run factors including natural disasters, political crisis and wars, inflation, and infectious diseases (Wu et al. 2012), which are particularly present in developing countries. The food price crises of 2007/08 and 2009/10, when international cereal prices increased two- to three-fold and more than 100 million people were driven into poverty and became malnourished, were largely triggered by short-run overshooting forces including trade events (Götz et al. 2013; Headey 2011). However, also, long-run demand and supply factors such as a growing demand for biofuels, population growth, changing diets, slowing yield growth, and climate change are important explanations for the recent food crises, ‘moving the world from a lower to higher food-price regime’ at the very least (Headey 2011). Projections of food demand and supply indicate that the food crises herald a period of continued risk and uncertainties in food security, particularly for the poor people in low-income countries (Godfray et al. 2010). Some even see the world confronted with an ‘agricultural bomb’ because of the expected global food needs (Laurance et al. 2014).

Future food demand

Future agriculture must accommodate the higher food demand that is mainly driven by population increase in combination with income growth and resulting dietary changes. Projections about the future global population vary substantially (van Dijk and Meijerink 2014) because precise demographic developments are hardly predictable beyond two or three decades (Valin et al. 2014). However, most models driven by business-as-usual scenarios project between 8.2 and 9.5 billion people in 2050 (van Dijk and Meijerink 2014). Population growth is expected to occur mainly in developing countries accompanied with increasing urbanization. Baseline projections for the annual global GDP growth range from approximately 2.8% and 3.2% (van Dijk and Meijerink 2014), and incomes are expected to rise particularly in developing and middle-income countries. This increase is imperative to rescue people from poverty (Beddington 2010). However, rising affluence will lead to diets that include a larger share of livestock products, a nutrient transition law introduced by Bennett (1941). Globally, land devoted to livestock production already totals 3.73 billion hectares or 75% of total agricultural land (Foley et al. 2011), but demands for feed and fodder for animals will further increase because of the increasing demand for meat and dairy products, particularly in developing economies (Popkin et al. 2012).

Projections of future food demand increase from ten different global economic models ranges between approximately 62% and 98% by 2050, with an average demand increase of 74% (Valin et al. 2014). Projections of food demand are subject to large uncertainty due to different socioeconomic assumptions, calibration choices, and model use. However, all projections are higher than the often cited projection of a 54% demand increase by FAO (Alexandratos and Bruinsma 2012). Further, it has been demonstrated that the projected increase in food demand will trigger an increase in cropland by an average of almost 200 Mha without factoring in climate change and more than 300 Mha with the projected climate change and its negative effects on yields (Schmitz et al. 2014). However, there is large uncertainty inherent in the projections of future land use because of different rates of yield improvements for crops, different assumptions about potential cropland and the costs of land expansion, in addition to the uncertainty in projections of future food demand, as previously described. Therefore, better spatially-explicit data on the potentials to expand croplands and to improve crop yields are imperative to decrease model uncertainties.

Over a billion people are currently consuming more calories than required for healthy diets. Overnutrition is particularly an issue in the developed world, but the incidence of obesity and overweight is growing in fast-developing countries (Pretty and Bharucha 2014). Overnutrition and obesity have been associated with high intakes of meat and other animal products (Popkin et al. 2012). Moreover, 30-40% of global food production is currently wasted by pre-consumer losses in developing countries and post-consumer losses in developed countries (Smith 2013). Therefore, reduction of waste, overnutrition, and consumption of livestock products, as well as the introduction of smarter biofuel policies and technologies are important approaches to reduce the global food demand (Keating et al. 2014; Stehfest 2014; Tilman and Clark 2014). However, even for the unrealistic case that this demand-side ‘mega-wedge’ driver (Keating et al. 2014) is drastically reduced, higher food production is still imperative for meeting future food security.

Strategies to meet future food demand

Therefore, the question of how to increase agricultural output in order to achieve food security while minimizing adverse environmental impacts from land use is a key challenge for humanity. Current realized yield improvements occur too slowly to meet the increasing demands for agricultural products (Ray et al. 2013). Moreover, if adaptation is absent, climate change is expected to have strong negative effects on yields of major cereals (Rosenzweig et al. 2014).

One strategy for increasing agricultural output is to expand cultivated areas. Globally, only one-half of the suitable land for crop production was under cultivation in 2008 (Smith 2013), suggesting a large scope for cropland expansion. However, most of the remaining suitable land is covered by forests or other natural areas. Conversion would entail substantial environmental costs in terms of greenhouse gas (GHG) emissions and loss of biodiversity (Gibbs et al. 2010). Cropland expansion in the tropics incurs particularly high environmental costs, and the food production benefits of tropical deforestation are small because land productivity is typically low (Foley et al. 2011; West et al. 2010). Expanding cultivated areas to pastures or non-agricultural land outside the tropics may be one strategy to reduce pressures on tropical forests, although this approach also entails critical trade-offs for the provision of ecosystem services (Flynn et al. 2012; Poeplau et al. 2011). Nevertheless, potentially available additional cropland is limited when all ecological and socioeconomic constraints are considered (Lambin et al. 2013). It is important to identify hotspots, where cropland expansion would be associated with limited environmental costs and high food production benefits.

One interesting option is to reclaim previously cultivated but currently abandoned agricultural land where the infrastructure for agriculture is already in place. Global hotspots of abandoned agricultural land are in the Eastern and Midwestern United States, South America, India, China, and Australia (Cai et al. 2010; Campbell et al. 2008), as well as in the territory of the former Soviet Union (FSU) countries (Henebry 2009). However, abandoned cropland can host a range of ecosystem services and may provide habitats for species sensitive to land management (Queiroz et al. 2014). Moreover, abandoned cropland may sequester large amounts of carbon in response to natural succession after abandonment (Kurganova et al. 2014). Therefore, re-cultivation of abandoned land may contribute to the loss of biodiversity, jeopardize ecosystem services, and - where large carbon sinks are established - trigger carbon emissions. Thus, there is an important trade-off between food production and climate change mitigation. Processed-based, spatially-explicit models are useful to assess carbon fluxes due to land use/cover change and to estimate carbon emissions in response to re-cultivation of abandoned land.

The task to identify regions where cropland expansion would be associated with limited environmental costs is timely because agricultural land acquisitions are increasingly targeting the Global South. Since the food price crisis of 2007/08, governments started to secure property rights in foreign farmland. Moreover, the 2008 financial crisis has motivated investors to look for outlets in the agricultural sector (Arezki et al. 2013). Agricultural land acquisitions is frequently negatively referred to as a 'global land rush' or 'global land grabbing' because foreign or domestic investors often make use of weak or corrupt land governance and infringe on the access of smallholders to land and water without compensation (Borras et al. 2011). Moreover, land acquisitions often ignore biodiversity values and non-provisioning ecosystem services, such as carbon sequestration (Deininger et al. 2011).

A second promising strategy to increase food supply is to close yield gaps through the 'sustainable intensification' of the existing agricultural land (Pretty and Bharucha 2014). Total greenhouse gas emissions embodied in the sustainable intensification to close yield gaps and to further increase yield potentials are lower as if future demand would be met through conventional approaches including cropland expansion in poorer nations (Tilman et al. 2011). Yield gaps, i.e., the differences between potential and actual yields, are particularly large in developing and transition countries (Neumann et al. 2010). A recent global study based on a crop growth model found sizable wheat yield gaps in Eastern Europe, Russia, western parts of the United States, Western and Central Asia, Africa, and Australia (Balkovič et al. 2014). Drivers of yield gaps are interwoven and often differ from one region to another. Yield gaps occur because of limited inputs and technical constraints, but 'it is not as simple as farmers not being willing or able to adopt a set of technologies and practices' (Keating et al. 2014). High input prices, low returns, lack of information, and high risks (for example, due to volatile climate conditions) may make it undesirable for farmers to invest in yield-increasing measures that reduce the yield gaps. Substantial limitations in agricultural management, infrastructure, knowledge, and agricultural policies are often underlying causes for yield gaps.

Closing yield gaps is not environmental sustainable *per se*. Precision agriculture, i.e., more efficient use of nutrients and water, better use of crop residues, and less intensive tillage are important means towards more sustainable farming practices that balance higher yields and environmental costs (Burney et al. 2010; Chen et al. 2011; Spiertz 2012). Crop growth simulation models are useful tools to identify yield gaps at different spatial scales. Crop growth simulation models can also test various agronomic measures to increase yield and their environmental impacts (van Ittersum et al. 2013).

Socio-economic and agricultural changes after the dissolution of the Soviet Union

The dissolution of the Soviet Union (SU) in 1991 provided the opportunity for free-market systems, international trade and competition, as well as land reforms in the resultant nations (Csaki 2000; Lerman et al. 2004). Governmental regulation and support for agricultural production were substantially reduced compared with the Soviet era (Liefert and Liefert 2012; Prishchepov et al. 2013). Rural regions of Russia were hit particularly hard by the political and economic transition after 1991; GDP per capita decreased from almost 8,000 US$ in 1990 to 4,000 US$ in 1996, and the unemployment rate also drastically increased during the early 1990s (Stillman 2006). Per capita consumer income halved already in the first year after the dissolution (Liefert 2004), which contributed to the decline in consumption of meat and milk products. Beef consumption, for example, decreased from 32 kg/capita/year in 1990 (FAOSTAT data available for the SU only) to 15 kg/capita/year in 2000 in Russia (FAO 2014).

Decreasing consumption of livestock products, low productivity compared with internationals standards, and particularly the withdrawal of governmental subsidies to agriculture were the major drivers of the collapse of the livestock sector (Lioubimtseva and Henebry 2012). The Russian cattle stocks decreased by 65%, from 57 million in 1990 to 20 million in 2012 (ROSSTAT 2014). Worldwide, a similarly drastic decline in the number of cattle occurred in the United States after the mid-1970s (FAO 2014). The contraction of the livestock production caused a sharp decrease in the sowing area of fodder crops (27 Mha or 61%). The sowing area of grains other than wheat (for example, barley and rye), which are partly used as fodder for livestock, also decreased substantially between 1990 and 2012 (19 Mha or 51%). Therefore, the total decline of cropland area in Russia, 41 Mha between 1991 and 2010 (ROSSTAT 2014), was closely associated with to the collapse of the livestock sector. Consequently, since 1991, Russia has become one of the largest net importers of livestock products, particularly from Europe and South America (FAO 2014).

The dissolution of the SU and the subsequent withdrawal of agricultural subsidies as well as the liberalization of markets greatly reduced the ratio of the agricultural output prices to input prices and resulted in decreased input intensity (Rozelle and Swinnen 2004). Consequently, grain yields decreased after 1991. For example, the average winter wheat yields decreased from 1.93 t ha^{-1} between 1990 and 1992 to 1.49 t ha^{-1} between 1994 and 1996. The crop yields rebounded toward the late 1990s (FAO 2014), but remained much lower than the yields that were achieved in comparable natural conditions in other countries (FAO 2014).

Between 2008 and 2011, the average wheat yield in Russia was only 2.2 t ha^{-1}, which was rank 73 of 125 countries that reported wheat yields to the FAO; Russia followed Bangladesh and Paraguay. This rank is much lower than Russia's potential, demonstrated by the observation that wheat yields achieved in many western European countries were more than three times higher than in Russia during this period (FAO 2014). Among the main reasons for the low yields in wheat cultivation in Russia was low input intensity, particularly of irrigated water and fertilizers (Mueller et al. 2012; Rozelle and Swinnen 2004). Low input intensity was mainly caused by financial shortcomings and volatile climate conditions that translated into volatile returns in the absence of sound insurance systems to protect against low yields, institutional constraints, and adverse infrastructure (Bokusheva et al. 2011; Nosov and Ivanova 2011). Today, cropland is typically owned by large enterprises such as agroholdings and rural dwellers who tend to have limited motivation to increase land productivity (Trukhachev et al. 2014).

Study area – European Russia

European Russia, with a total area of four million km² (Figure I–1), was selected for this study because widespread abandoned agricultural lands and large yield gaps co-exist in this region (Balkovič et al. 2014; Prishchepov et al. 2013). Please note that Ukraine and Belarus are captured in chapter II but not in chapters III and IV. European Russia likely offers ample scope both for land expansion of agricultural area and intensification of agricultural production per unit area, thereby contributing to satisfying the increasing global demands for agricultural products. Moreover, Russia remains heavily dependent on imports of livestock products, particularly from South America, where enormous environmental costs accompany agricultural production; increased agricultural production in Russia could therefore reduce the environmental costs embodied in trade to Russia and may also benefit Russian farmers and consumers.

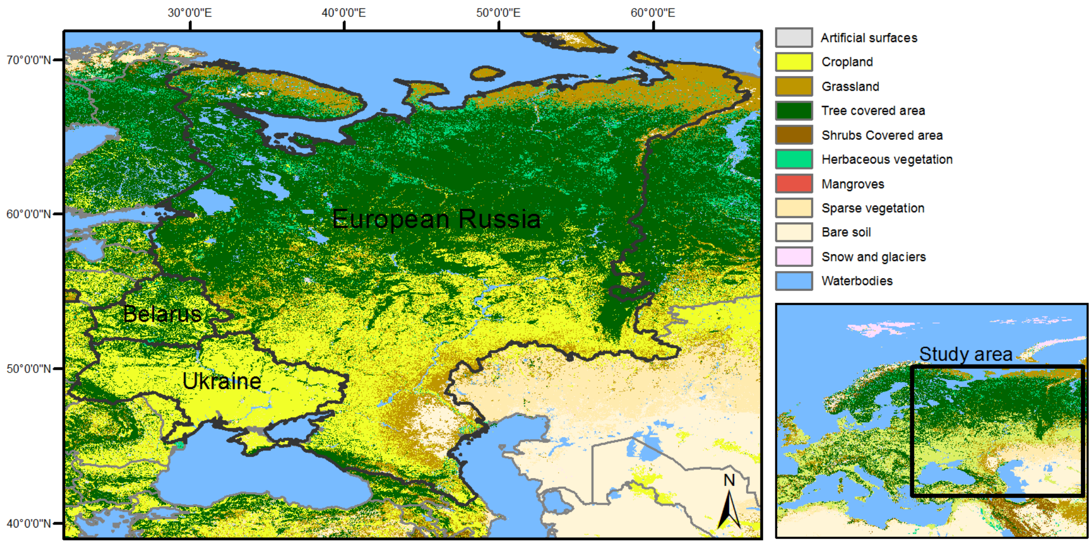

Figure I-1: Study area and land cover. Data source: Global Land Cover-SHARE of year 2014 (Latham et al. 2014).

Increased agricultural production in Russia may come at considerable environmental cost. For example, large carbon sinks typically developed on the idle land, and the re-use of these lands may lead to sizable carbon emissions (Kurganova et al. 2014; Vuichard et al. 2008). Moreover, closing yield gaps through input intensification will be associated with an unprecedented amount of additional energy needs. Therefore, it is not only important to estimate the extent of abandoned agricultural land and the size of regional yield gaps but also to assess the environmental trade-offs of increasing agricultural production in European Russia.

This is of particular and timely relevance, because agricultural land acquisitions has increasingly targeted the FSU countries (Visser and Spoor 2011). Although largely unnoticed so far, the extensive agricultural land resources in European Russia – the abandoned fields in particular - are increasingly under demand by domestic (mainly by so-called oligarchs, who run agroholdings) and, secondary, by foreign land investors (Steggerda and Visser 2012; Visser and Spoor 2011). The grabbed area by foreign investors in Russia was 2.83 Mha in 2012, according to Rulli et al. (2013). However, the number, extent, and spatial pattern of land acquisitions in the FSU are not well known, mainly because of incomplete or non-existing statistics (Visser and Spoor 2011). Therefore, the environmental as well as the socioeconomic implications of recent and of future land acquisitions in Russia are still largely unclear.

Given the rising demand for farmland in the FSU, spatially explicit data of the extent of abandoned agricultural land and the sizes as well as spatial distributions of yield potentials and yield gaps are imperative to better evaluate the environmental and social trade-offs involved in increasing agricultural production. Unfortunately, reliable spatially explicit data on abandoned agricultural lands were only available for a few regions in Russia (Prishchepov et al. 2013). Global applications of crop growth models have identified large yield gaps for Russia (Balkovič et al. 2014), but the results are likely tainted with considerable uncertainty, mainly because of coarse or inaccurate input data. Thus, these models are of limited suitability for decision makers in Russia. Therefore, neither the rates and spatial pattern of cropland abandonment and the associated carbon fluxes nor the yield gaps are well known in European Russia.

Further, we selected European Russia because this region is one of the most important breadbaskets worldwide. The European region of Russia contained 72% or 55.7 Mha of the total sowing area of Russia (77 Mha) in 2011 (ROSSTAT 2014). This region also accounts for 75% of Russia's wheat production and provides the bulk of Russian wheat exports (ROSSTAT 2014). Furthermore, European Russia has access to the Black Sea and its important grain terminals for exporting production. Thus, it is well connected to world grain markets. European Russia harbors the most important agro-industrials centers of Russia; the bulk (85%) of the Russian population lives in the European part of Russia.

The northern croplands of European Russia are small (Figure I–1) and are characterized by temperate continental climate, according to the Köppen-Geiger classification (Peel et al. 2007), with stable and sufficient precipitation (500-700 mm) for crop production. Extremely cold winters, short growing periods, and mostly infertile podzolic soils limit the potential for higher crop yields in the northern regions of European Russia. A cold semi-arid climate with lower and more volatile precipitation, but longer growing periods and mostly fertile soils, such as Chernozems (black earth soils), characterize the southern and southwestern regions of European Russia.

Research questions

The primary objective of this dissertation was to systematically quantify the untapped agricultural potentials in European Russia. To this end and, given the aforementioned research gaps, this dissertation aimed at to address three research questions, separated into three chapters. Figure I–2 illustrates the main methodological approaches developed or applied, the dissertation objectives, and how the three chapters are methodologically connected.

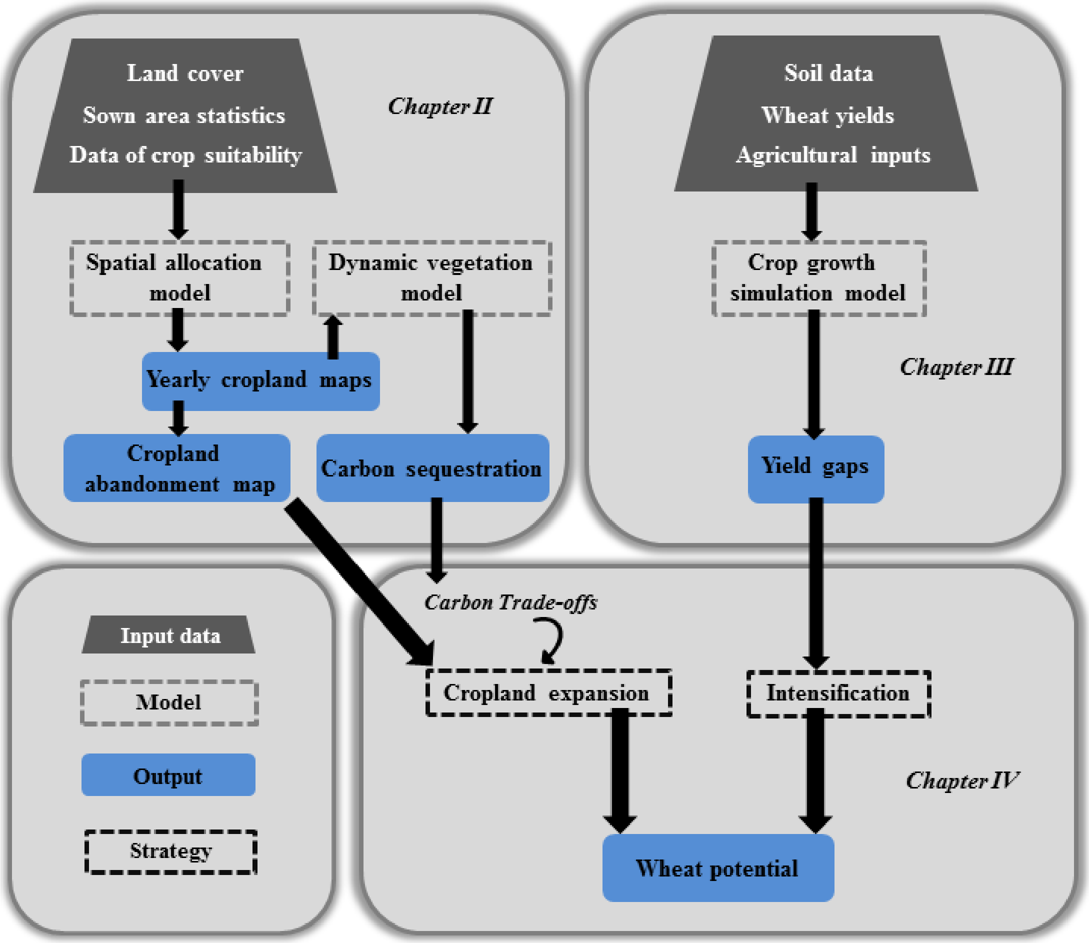

Figure I-2: Flow chart of this dissertation.

Research Question I (Dissertation chapter II): What were the spatial and temporal patterns of cropland change and how large are the carbon fluxes due to post-Soviet cropland change?

Remote sensing is a key method for monitoring and quantifying rates and spatial patterns of land-cover/use change. However, complex classes such as agricultural abandonment, which is often spectrally similar to other semi-natural land cover, complicate the development of an accurate map of land-cover/use change using remote sensing. Chapter II utilized agricultural statistics on sown areas and biophysical proxies for cropland suitability as inputs in a spatially explicit cropland allocation model to produce yearly cropland maps for European Russia, Ukraine, and Belarus (Figure 1–2). Validation of the results was performed based on the interpretation of very high-resolution imagery available in Google Earth. This approach yielded the first cropland maps with annual resolution for European Russia, Ukraine, and Belarus, which also captures the time elapsed since abandonment. We fed the yearly cropland maps into the dynamic vegetation model LPJmL to investigate the spatiotemporal dynamics and patterns of carbon fluxes due to cropland change after the dissolution of the SU in 1991. Simulating carbon dynamics due to cropland abandonment is imperative to assess the trade-offs between increasing food production (through land expansion) and carbon sequestration through continued natural succession. However, land intensification of the existing cropland is also an important option to increase agricultural output. Therefore, Chapter III investigates the following question:

Research Question II (Dissertation chapter III): How large are the yield gaps in wheat production in Russia?

To date, global studies indicated large yield gaps for Russia, but both local and regional studies are lacking. This is unfortunate because food benefits through closing of yield gaps seem to be high, but policy makers do not yet have proper information on the size and distribution of yield gaps and which management strategies are needed to close them. Therefore, Chapter III tested the utility of a crop growth simulation model to simulate potential wheat yields and yield gaps for the key wheat growing areas across European Russia (Figure 1–2). We used the erosion productivity impact calculator (EPIC) that was integrated into the model applied for this dissertation (the soil and water assessment tool, SWAT). Chapter III tested the SWAT Calibration and Uncertainty Program (SWAT-CUP) in its ability to conduct model calibration, model validation, and uncertainty assessments. Thereby, various global and regional agricultural datasets as well as data sets on geophysical characteristics were integrated into SWAT-CUP. Using the calibrated models, Chapter III investigated both the single and the combined effects of nitrogen fertilizer and irrigation on wheat yields.

Research Question III (Dissertation chapter IV): How large is the potential for Russia to increase its wheat production?

The cropland abandonment and yield gap data, developed in chapters II and III of this dissertation, respectively, allowed quantification of the potential for wheat production through cropland expansion to abandoned cropland and land intensification by closing yield gaps in European Russia (Figure I–2). Chapter IV considers the carbon trade-offs that are associated with cropland expansion and assessed the question of whether European Russia can expect higher wheat production from cropland expansion and/or from land intensification. Finally, Chapter IV discusses the structural problems and obstacles for the agricultural sector in Russia that contributes to the idle production potentials.

Structure of this dissertation

This dissertation consists of five chapters (I-V). This introduction (I) is followed by three research chapters (II-IV) that are published in international peer-reviewed journals. The following three research chapters have been outlined in the previous section:

Chapter II: Schierhorn, F., Müller, D., Beringer, T., Prishchepov, A.V., Kümmerle, T., & Balmann, A. (2013). Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus. *Global Biogeochemical Cycles, 27*, 1175-1185.

Chapter III: Schierhorn, F., Faramarzi, M., Prishchepov, A., Koch, F., Müller, D. (2014): Quantifying yield gaps in wheat production in Russia, *Environmental Research Letters*, Vol. 9, No. 8.

Chapter IV: Schierhorn, F., Müller, D., Prishchepov, A., Faramarzi, M., Balmann, A. (2014): The potential of Russia to increase its wheat production through cropland expansion and intensification, *Global Food Security*, Vol. 3, No. 3-4, S.133-141.

Chapter V: Synthesizes the three research chapters and provides answers to the research questions posed in the introduction. Moreover, the main conclusions are drawn.

Chapter II Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus

Global Biogeochemical Cycles, 27 (2013), 1175-1185.

Florian Schierhorn, Daniel Müller, Tim Beringer, Alexander V. Prishchepov, Tobias Kümmerle, and Alfons Balmann

Abstract

Widespread cropland abandonment occurred after the collapse of socialism across the former Soviet Union, but the rates and spatial patterns of abandoned lands are not well known. As a result, the potential of this region to contribute to global food production and estimates of the carbon sink developing on currently idle lands are highly uncertain. We developed a spatial allocation model that distributes yearly and subnational sown area statistics to the most agriculturally suitable plots. This approach resulted in new, high-resolution (1 km^2) annual time series of cropland and abandoned lands in European Russia, Ukraine, and Belarus from 1990 to 2009. A quantitative validation of the cropland map confirms the reliability of this data set, especially for the most important agricultural areas of the study region. Overall, we found a total of 87 Mha of cropland and 31 Mha of abandoned cropland in European Russia, Ukraine, and Belarus combined, suggesting that abandonment has been severely underestimated in the past. The abandonment rates were highest in European Russia. Feeding our new map data set into the dynamic vegetation model LPJmL revealed that cropland abandonment resulted in a net carbon sink of 470 TgC for 1990 to 2009. Carbon sequestration was generally slow in the early years after abandonment, but carbon uptake increased significantly after approximately 10 years. Re-cultivation of older abandoned lands would be associated with high carbon emissions and lead to substantial amounts of carbon not being sequestered in vegetation formations currently developing on idle croplands. Our spatially and temporally explicit cropland abandonment data improve the estimation of trade-offs involved in reclaiming abandoned croplands and thus in increasing agricultural production in this globally important agricultural region.

Introduction

The surging demand for food and feed during the 20th century has been met by large production increases in agriculture (Foley et al. 2007), but this has come at substantial environmental costs. For example, humans currently appropriate nearly a quarter of the Earth's terrestrial net primary productivity (Haberl et al. 2007), and land use accounts for about a third of global GHG emissions. Moreover, global population growth and changing consumption patterns are likely to double global food demand by 2050 (Cirera and Masset 2010; Godfray et al. 2010; OECD-FAO 2010), and ambitious renewable energy targets are currently formulated (Fargione et al. 2008). The question of how to increase agricultural output while mitigating emissions from land use is therefore a key challenge for humanity (Foley et al. 2011).

One prominent strategy for increasing agricultural production is to expand cultivated areas into native ecosystems, such as in many parts of the tropics. However, most suitable arable land is already under cultivation (Lambin and Meyfroidt 2011; Ramankutty et al. 2008), and converting unused productive land, particularly in the tropics, will cause significant GHG emissions (Foley et al. 2005; Gibbs et al. 2010; Tan et al. 2009; West et al. 2010) and diminish carbon sequestration (Post and Kwon 2000; Stoate et al. 2009; Tilman et al. 2002). Land expansion into previously uncultivated areas is therefore unlikely to be a sustainable approach to increasing the supply of agricultural products.

An alternative is to reclaim previously cultivated but currently abandoned agricultural land. The largest areas of abandoned agricultural land have been observed in the Eastern and Midwestern United States, Brazil, Argentina, Western Europe, India, China, and Australia (Cai et al. 2010; Campbell et al. 2008), as well as in the territory of the former Soviet Union (FSU) countries (Henebry 2009). However, re-cultivation often requires significant investments, depending on the type of successional vegetation, the time elapsed since abandonment, and economic and institutional constraints affecting the profitability of farming (Larsson and Nilsson 2005; USDA-FAS 2008). Moreover, depending on the soil properties, climate conditions, and the time since abandonment, which are the main determinants of natural succession after abandonment, abandoned land may sequester significant amounts of carbon (Kuemmerle et al. 2011; Rhemtulla et al. 2009), and re-cultivation is likely to be associated with considerable GHG emissions (Guo and Gifford 2002; Vuichard et al. 2008). Understanding the spatial patterns, biophysical characteristics and land use history of abandoned cropland are therefore important in identifying areas where re-cultivation is associated with modest carbon emissions.

The collapse of the Soviet Union triggered the most drastic episode of land use change in the 20th century, most importantly the widespread abandonment of agricultural land (Henebry 2009). Available agricultural statistics on sown areas suggest that approximately 50 million ha (Mha) of cropland were abandoned after 1990 in Russia, Ukraine, and Belarus (BELSTAT 2004; ROSSTAT 2014; UKRSTAT 2009). These vast, currently unused land resources suggest large untapped agricultural production potential (Lambin and Meyfroidt 2011; Liefert et al. 2010), which could be of great importance for global food production and mitigation of land use pressure in other parts of the world, in the light of increasing global competition for land.

The large extent of agricultural land abandonment in Russia, Ukraine, and Belarus, as well as the suitable biophysical conditions for natural succession, has triggered significant carbon sequestration to date. By integrating global land use data covering the time span from 1991 to 2000 into a process-driven ecosystem model, it was estimated that the abandonment of agricultural lands of the FSU resulted in a total carbon sequestration of up to 64 TgC (Vuichard et al. 2008). According to field measurements, total carbon sequestration due to agricultural land abandonment was between 585 and 870 TgC (Kurganova et al. 2013). One important question is why there are such large differences between the estimates. In short, the estimates of carbon sequestration due to cropland abandonment differ widely because of inconsistent methods and models, different time periods, and most importantly because of outdated and divergent statistics on agricultural land abandonment (Dolman et al. 2012).

Quantifying agricultural production potentials and the carbon trade-offs of re-cultivation is hampered by incomplete knowledge of the quantity and location of cropland changes since the collapse of the Soviet Union. While a variety of satellite-based global land cover maps exists (Bartholomé and Belward 2005; Bicheron et al. 2008; Friedl et al. 2002; Hansen et al. 2000; Loveland et al. 2000), these maps differ substantially for the FSU and do not contain information on abandoned agricultural land. Combining satellite-derived land cover products with agricultural inventory data is an important alternative, but existing global maps also differ greatly for the FSU (Erb et al. 2007; Klein Goldewijk 2001; Leff et al. 2004; Pittman et al. 2010; Portmann et al. 2010; Ramankutty et al. 2008). As a result, reliable spatiotemporal data on contemporary and abandoned croplands are not available for most parts of the FSU. This is unfortunate, given the importance of reliable land use and land cover data in capitalizing on the idle agricultural potential of FSU countries and assessing carbon sequestration due to cropland abandonment and carbon emissions associated with re-cultivating abandoned lands.

Our main goal in this study was to map the cropland extent for each year since 1990, which would make it possible to estimate the extent and duration of abandonment and re-cultivation since the collapse of socialism and quantify carbon fluxes on cropland. To do this, we developed a spatially explicit cropland allocation model to produce yearly cropland maps for European Russia, Ukraine, and Belarus. We used the yearly cropland data to calibrate a dynamic global vegetation model (the Lund-Potsdam-Jena managed Lands or LPJmL model) to assess rates, spatial patterns, and the total quantity of carbon sequestration due to cropland abandonment.

Data and methods

The allocation routine combines global land cover data, agricultural inventory statistics as well as data sets on geophysical characteristics and accessibility to map annual cropland cover. The cropland maps are then fed into LPJmL to estimate carbon fluxes (Figure II–1).

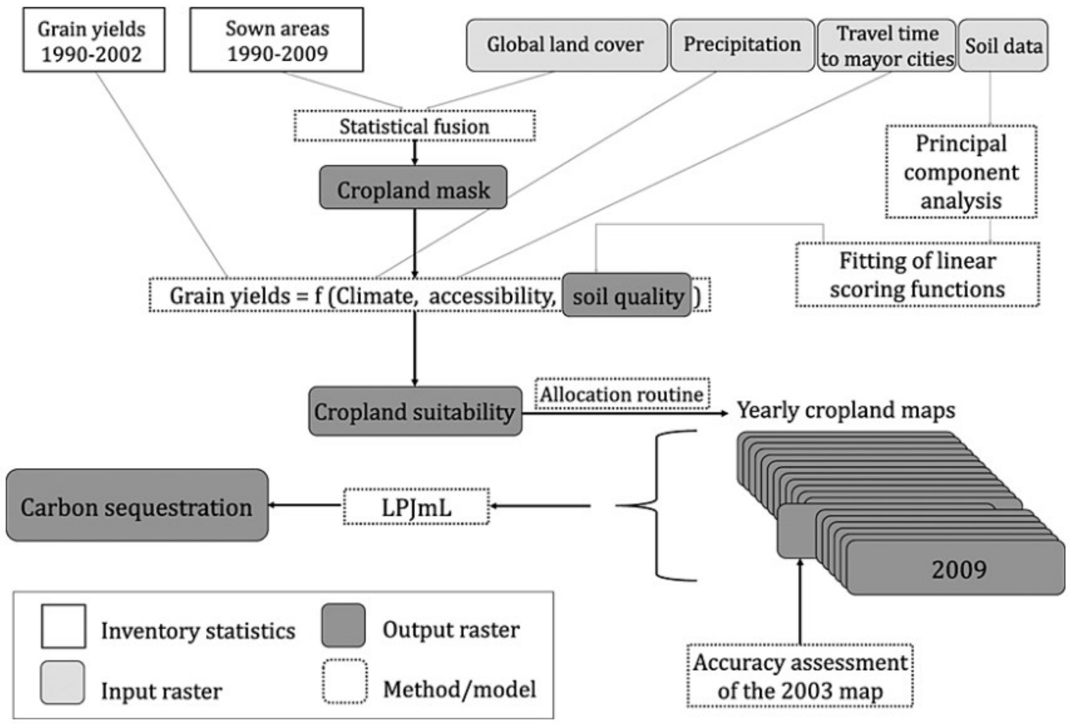

Figure II-1: Method flowchart.

Cropland mask from global land cover data

We applied a statistical fusion procedure similar to that used by Ramankutty et al. (2008) to generate a binary cropland mask that separates potential locations of cropland from grasslands and other seminatural land cover/use classes. This procedure is a combination of satellite-based global land cover data sets, namely, Global Land Cover 2000 (GLC2000) (Bartholomé and Belward 2005), MODIS Land Cover (Friedl et al. 2002), and GlobCover (Bicheron et al. 2008), and subnational statistics on sown area (details of this procedure are outlined in the Text S II-1). The cropland mask is a conservative cropland representation because we ensured that the amount of cropland covered by the mask exceeds the reported cultivated areas for all regions and all years by at least 20% (see Text S II-1). The spatial allocation model distributes yearly sown area statistics on observations identified as cropland in the cropland mask based on plot suitability.

Agricultural inventory statistics

Most global cropland maps to date have been based on agricultural inventory statistics from the Food and Agriculture Organization of the United Nations (FAO). For the FSU, however, FAO data are problematic because they fail to capture large amounts of abandoned cropland (Figure II–2) and thus overestimate currently cultivated lands. For example, for Russia, the country with the highest cropland abandonment rates of the FSU, global land use maps based on FAO indicate 125 Mha of cropland (Table II-1). According to Russian statistics on sown areas, this is an overestimation of more than 45 Mha.

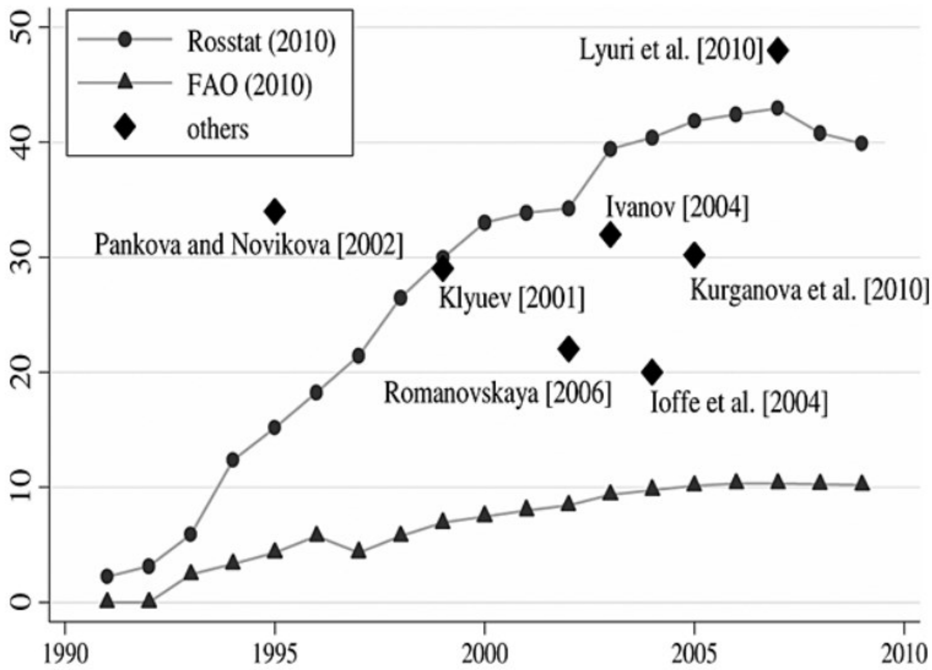

Figure II-2: Cropland abandonment in Russia from various sources. Note that ROSSTAT (2014) shows cumulative cropland abandonment and FAO (2014) shows cumulative abandonment of arable land and permanent crops. The diamonds indicate independent point estimates of abandoned cropland. Additional information on source, period/year, and labels of abandonment estimates can be found in Table S II–2.

Table II-1: Previous Estimates of Cropland Extent for Russia, Ukraine, and Belarus (Mha).

Source	Year	Label	Asian Russia	European Russia	Sum Russia	Ukraine	Belarus
Ramankutty et al. (2008)	1993	Cropland	36.70	87.59	124.29	33.98	6.16
Portmann et al. (2010)	~2000	Cropland	21.76	57.38	79.13	27.68	6.11
Biradar et al. (2009)	~2000	Cropland			128.67	31.28	11.05
Klein Goldewijk et al. (2011)	2000	Cropland	45.80	77.78	123.58	33.24	5.60
Erb et al. (2007)	2000	Cropland	37.83	88.32	126.16	33.42	6.29
FAO (2014)	2009	Arable land and permanent crops			123.54	33.38	5.66
BELSTAT (2004)	2003	Sowing area					5.56
UKRSTAT (2009)	2008	Sowing area				30.89	
ROSSTAT (2014)	2009	Sowing area	26.85	50.96	77.81		

Source	Year	Label	Asian Russia	European Russia	Sum Russia	Ukraine	Belarus
Bartholomé and Belward (2005)	2000	Cropland	21.98	64.58	86.56	27.78	3.77
		Forest - cropland complexes	5.79	20.63	26.42	6.68	3.65
		Cropland - grassland complexes	14.79	27.08	41.87	9.51	2.85
		SUM	42.56	112.30	154.85	43.97	10.27
Friedl et al. (2002)	2000	Cropland	29.02	101.66	130.68	43.59	7.40
		Cropland/natural vegetation mosaic	31.05	33.01	64.05	6.68	5.11
		SUM	60.07	134.67	194.74	50.27	12.51
Bicheron et al. (2008)	2005	Rainfed croplands	8.29	34.06	42.35	15.38	3.11
		Mosaic cropland (50–70%) / vegetation (grassland/shrubland/forest) (20–50%)	25.61	57.26	82.87	20.96	4.85
		Mosaic vegetation (grassland/shrubland/forest) (50–70%) / cropland (20–50%)	15.38	23.19	38.57	8.88	2.18

Source	Year	Label	Asian Russia	European Russia	Sum Russia	Ukraine	Belarus
		SUM	49.27	114.51	163.79	45.22	10.14

We assessed the quality of the Russian sown area data by validating official agricultural inventory statistics on sown areas (ROSSTAT 2014) for all districts of two provinces (Kaluga and Rjazan) with Landsat-based abandonment and cropland maps (Prishchepov et al. 2012). The validation of these data showed very good agreement (Pearson $R^2 = 0.74–0.86$). Good agreement with other independent estimates for cropland abandonment further corroborates the reliability of sown area data from official agricultural inventory statistics (Figure II–2), which was also reported by Ioffe et al. (2004). We assume that the sown area data from national official agricultural inventory statistics in Ukraine (UKRSTAT 2009) and Belarus (BELSTAT 2004) are also the best data available. To the best of our knowledge, these data have previously not been used to produce global cropland maps or to derive cropland abandonment maps. Sown area statistics were available for all 80 provinces (oblasts) of European Russia and Ukraine, covering the time spans from 1940 to 2009 and from 1940 to 2008, respectively (Table S II-1). Missing years in the statistics between 1940 and 1990 were approximated using spline interpolation. For Belarus, we obtained sown area statistics for all six provinces for the period from 1990 to 2003 (Table S II-1).

We also obtained grain yield data for 2173 districts (*rayons*) for multiple years between 1990 and 2009 (Table S II-1). We omitted grain yield data from drought years, computed the area-weighted mean of grain yields from nondrought years at the district level, and thus finally obtained an estimate of habitual grain yields. For identification of drought years, we used the hydrothermal coefficient (HTC, Dronin and Kirilenko 2008), which is an index of annual drought severity that integrates daily average temperature and precipitation data over the growing season (see the Text S II-2 for more details).

Geophysical variables and accessibility

Using daily gridded precipitation data at a spatial resolution of 0.5° (Schuol and Abbaspour 2007), we estimated annual precipitation sums over the growing period (reported by the U.S. Department of Agriculture (USDA), USDA 2013), the time when precipitation most effectively triggers crop growth. We then computed the area-weighted mean annual precipitation for the nondrought years (indicated by the HTC; see above) at the provincial level for 1990 to 2009.

Likewise, soil quality is a key biophysical determinant of agricultural suitability. We used soil maps from the Harmonized World Soil Database (HWSD, Fischer et al. 2008), available at *http://www.iiasa.ac.at/Research/LUC/External-World-soil-database*) at a spatial resolution of approximately 1 km. The details of the generation of the soil quality map are outlined in the Text S II-3.

The physical accessibility of a plot to nearby market centers is a strong indicator of the degree of marginality (Schneider et al. 2011) and of agricultural land change before and after the collapse of the Soviet Union (Ioffe and Nefedova 2004; Prishchepov et al. 2013). If the distance to markets increases, the ratio of output to input prices deteriorates due to increasing transportation costs, which reduces the profitability of agriculture. In addition, poor accessibility in post-Soviet landscapes typically correlates with low soil fertility and lower rural population densities (Ioffe and Nefedova 2004). We measured market access as the travel time to the nearest major towns at a spatial resolution of 30 arc seconds using a map of travel times to major cities (Nelson 2008, available at *bioval.jrc.ec.europa.eu/products/gam/index.htm*). Both the geophysical and the accessibility variables were assumed to be time invariant. We masked all data sets to the same spatial extent, resampled them to a spatial resolution of 1 km, and projected them to an Albers Equal Area coordinate system.

Mapping cropland suitability

Spatial regression analysis is frequently used to derive the suitability of a plot of land for specific land use activities (Overmars et al. 2007; Verburg et al. 2006). To map cropland suitability, we related grain yields to mean soil quality, travel time to major cities, and precipitation during the growing season for all 2.173 districts in European Russia, Ukraine, and Belarus.

Global regression models are not well suited for deriving land suitability because they are unable to capture the substantial spatial variability that characterizes the study area. For example, summer precipitation is decisive for grain yields in the southern parts of European Russia, where grain yields are restricted by shorter growing periods (Dronin and Kirilenko 2008). Likewise, soil quality is heterogeneous across the study region and has a crucial impact on the spatial variation of the grain yields. To account for this spatial variation, we partitioned the study area into the three prevalent major habitat types, i.e., biomes (Olson et al. 2001, Pontic steppe, mixed forest and forest steppe, Taiga; see Figure S II 1, left). We assigned each province to the biome that has the largest area share in the province (Figure S II–1, right). For each biome, we estimated separate ordinary least square (OLS) regressions of grain yields at the district level. Because Lagrange multiplier tests confirmed spatial dependency, we also calculated spatial error and spatial lag models with the same set of dependent and independent variables (Anselin 1988). We therefore estimated nine regression models (i.e., standard OLS, spatial error, and spatial lag models for three biomes). Diagnostic tests showed that the spatial lag model best accounted for spatial dependencies and had the best fit Table S II–3); hence, we used these models for mapping cropland suitability. Grain yields in these models were positively correlated ($p < 0.1$) with soil quality and negatively correlated with the travel time to major cities in all three biomes, as expected (Table S II–3). Precipitation exerted a significantly positive effect on grain yields in the mixed forest and forest steppe as well as in the Pontic steppe, but was negatively associated with grain yields in the Taiga biome. We used the regression results to predict grain yields at the district level and compared the predictions to observed yields for each biome (Figure S II–2). Finally, we multiplied the coefficients from the spatial lag models with the independent variables and the spatial lag term at the 1 km^2 grid level to obtain probability maps of grain yields, which we used as a proxy for cropland suitability (Figure S II –3, right).

Spatial allocation routine

The biophysical characteristics of a location, natural suitability for agriculture, and physical access affect transportation costs. We assumed that cropland change during the Soviet period (mainly cropland expansion) and after the collapse of the Soviet Union (mainly cropland abandonment) are mainly determined by cropland suitability and that the least suitable plots are the first to be abandoned (Ioffe and Nefedova 2004; Prishchepov et al. 2013). Hence, our allocation algorithm distributed the sown areas for each year to the most suitable locations for the cultivation of crops in the study area, resulting in yearly maps of sown areas.

Our allocation algorithm distributed sown areas for each year since 1750 to the most suitable location for the cultivation of crops, resulting in yearly cropland maps. For 1940 to 2009, we used official agricultural inventory statistics on sown areas (see 2.2). Sown area statistics were not available from 1750 to 1939 and we used the HYDE 3.1 database (Klein Goldewijk et al. 2011) to approximate yearly sown areas for this period. We considered locations as abandoned if the land use changed from cultivation to any other land use from one year to the next. We ignored intermediate fallow operations and transitions from cropland to managed grassland because the proportion of fallow land is relatively constant over time and the extent of transitions from cropland to managed grassland is negligible (Ioffe and Nefedova 2004). The dramatic contraction of the livestock sector in Russia after 1990 (FAO 2014) suggests only minor conversions from managed cropland to managed grasslands and, if so, as an intermediate stage preceding abandonment.

Accuracy assessment

Very high-resolution (VHR) imagery available in Google Earth (http://earth.google.com) is a valuable data source for validating land cover maps, especially for large areas for which ground-based data collection is not feasible (Biradar et al. 2009; Clark et al. 2010; Fritz et al. 2011; Pittman et al. 2010). To assess the reliability of our cropland map, we focused on the year 2003, because the latest statistics on sown area available for the entire study were from this year. We randomly selected 1546 pixels proportional to the share of cropland and noncropland in 2003 in each ecoregion. Ecoregions are nested within biomes and characterized by distinct natural communities, geographical properties, and ecological processes (Olson et al. 2001). To avoid spatial autocorrelation, we used a minimum distance of 10 km between points (Figure S II–4). Two interpreters independently labeled each point as cropland or noncropland. Each interpreter estimated the percent of cropland within the sampled pixels in 10% intervals. Estimates of cropland shares of 50% or larger were labeled as “cropland” and all others as “noncropland.” When the two interpreters differed in their assessment (i.e., what was labeled as cropland by one interpreter was not by the other), a third independent interpreter was asked to label the point to reach a majority decision. Using this validation data set, we calculated the overall accuracy and the users' and producers' accuracy for the 2003 cropland map (Foody 2002). We did not validate the cropland abandonment class because identifying abandoned fields based on single-date imagery is challenging due to the complex and place-dependent spectral signature of abandoned cropland.

Simulating carbon dynamics

Dynamic vegetation models are excellently suited to quantifying the gross and net ecosystem responses to environmental changes (Cramer et al. 2001). The LPJmL model, a well-established dynamic vegetation model, simulates key ecosystem processes, including photosyndissertation (Collatz et al. 1992; Farquhar et al. 1980), plant and soil respiration, carbon allocation, evapotranspiration, and phenology in natural ecosystems, croplands, and pastures (Bondeau et al. 2007; Gerten et al. 2004). Nine plant functional types (PFTs) represent natural vegetation at the level of biomes (Sitch et al. 2003). LPJmL is well suited for our purposes because it also includes 12 crop functional types representing the most important economic crops (Bondeau et al. 2007). LPJmL is able to reproduce key features of the global carbon cycle (Jung et al. 2008), water cycle (Gerten et al. 2004; Wagner et al. 2003), vegetation patterns (Cramer et al. 2001; Hickler et al. 2008), plant phenology (Lucht et al. 2002), and fire patterns (Thonicke et al. 2001). LPJmL also includes CO_2 sensitivity within the range of free-air CO_2 enrichment (FACE) experiments (Gerten et al. 2004; Hickler et al. 2008).

For this study, we calibrated LPJmL with the Climate Research Unit's (CRU) time series (TS) 3.1 data for temperature and cloud cover (Mitchell and Jones 2005) and the Global Precipitation Climatology Centre's (GPCC) gridded precipitation data (version 5) (Rudolf et al. 2010). Land uses and land use changes were prescribed using the cropland maps for European Russia and Ukraine developed in this study (we excluded Belarus because statistical data after 2003 were not available). Because the legacy of past land use can have strong effects on carbon budgets (Kuemmerle et al. 2011; Rhemtulla et al. 2009), we initiated our LPJmL model runs in 1750. We calculated carbon sequestration on former agricultural land as the difference between the simulated land carbon stocks with and without land abandonment. In the presentation and interpretation of results, we focus on cropland abandonment and carbon sequestration since 1990 because most cropland abandonment occurred after the collapse of the Soviet Union.

Results

Cropland maps

Cropland covered 50.96 Mha in European Russia in 2009, 30.89 Mha in Ukraine in 2008, and 5.56 Mha in Belarus in 2003 (BELSTAT 2004; ROSSTAT 2014; UKRSTAT 2009). These numbers are considerably lower than most previous estimates of cropland for the study region (Table II-1).

Our allocation model produced cropland maps with a spatial resolution of 1 km and a yearly temporal resolution from 1990 to 2009 for European Russia, from 1990 to 2008 for Ukraine, and from 1990 to 2003 for Belarus. Based on the regression results, cropland was allocated in areas close to markets, with favorable soil conditions and higher precipitation. Figure II–3 (left) reveals high densities of cropland in southern Russia and Ukraine where the East European forest steppe and the Pontic steppe are located (42% and 35% of total land area in 2008, respectively, see Figure II–4 and Figure S II–1). Moreover, the 2008 cropland map Figure II–3 (left) shows the lower cropland density toward northern Belarus and European Russia. For example, in 2008, cropland density in the Scandinavian and Russian taiga and the Sarmatic mixed forest ecoregions was only 3% and 11% of total land area, respectively.

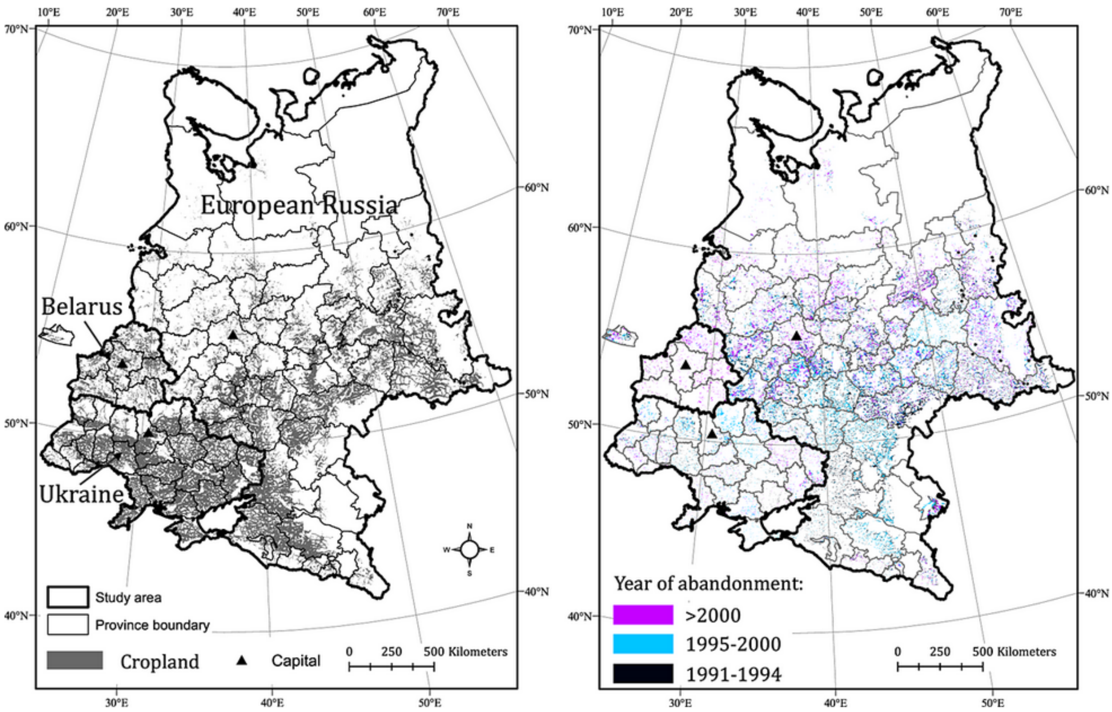

Figure II-3: Distribution of (left) cropland and (right) abandoned cropland. Note that the map at left represents cropland in 2009 for European Russia, 2008 for Ukraine, and 2003 for Belarus. The (right) colors indicate the duration of abandonment from 1990 to 2009 (European Russia), 1990 to 2008 (Ukraine), and 1990 to 2003 (Belarus).

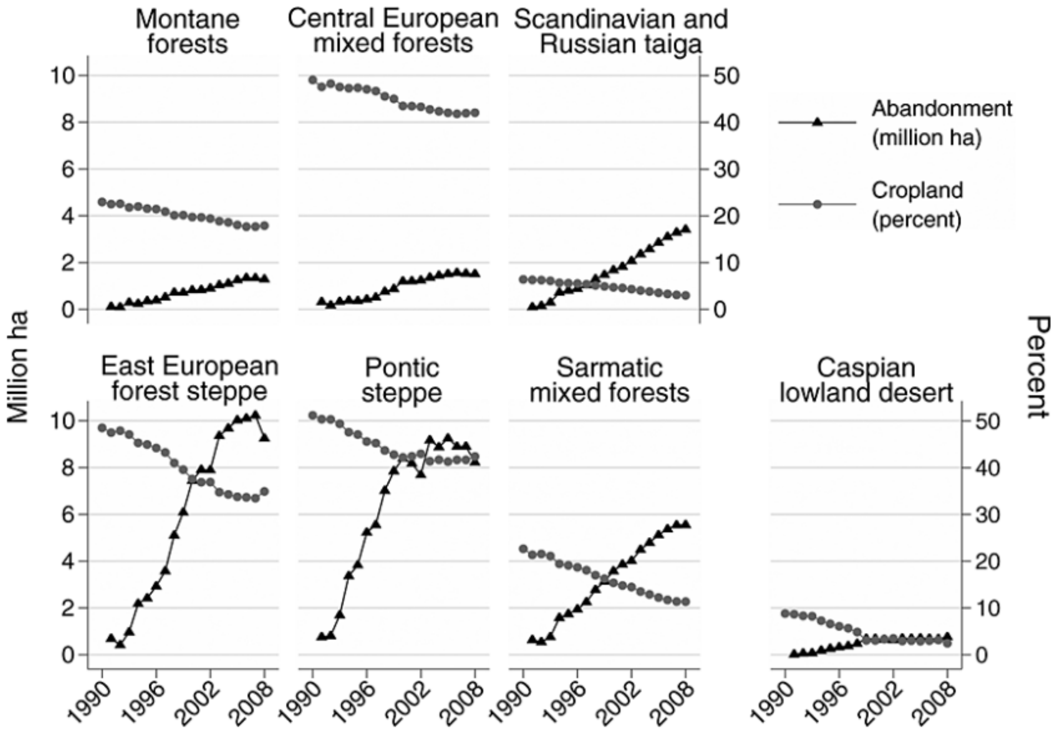

Figure II-4: Cropland abandonment (Mha) and cropland (percent of total land) by ecoregion. Note that Belarus is excluded because of missing data for cultivated area statistics. Accuracy assessment of the 2003 cropland map.

The validation of the 2003 cropland map revealed an overall accuracy of 65%, with a producer accuracy of 55% and a user accuracy of 56% (Table S II–3). The accuracy of the cropland maps differs significantly among ecoregions (Figure II–5). Most importantly, the ability of the allocation model to differentiate between cropland and noncropland was higher for the ecoregions that cover the most important agricultural regions of Russia and Ukraine. For these breadbasket regions, the producers' and users' cropland accuracies were 64% (East European forest steppe), 63% (Pontic steppe), 64% (East European forest steppe), and 59% (Pontic steppe). In the northern and temperate ecoregions, the uncertainties were larger, arguably due to the low proportion of cropland in the total land area and the dominance of mixed land cover classes.

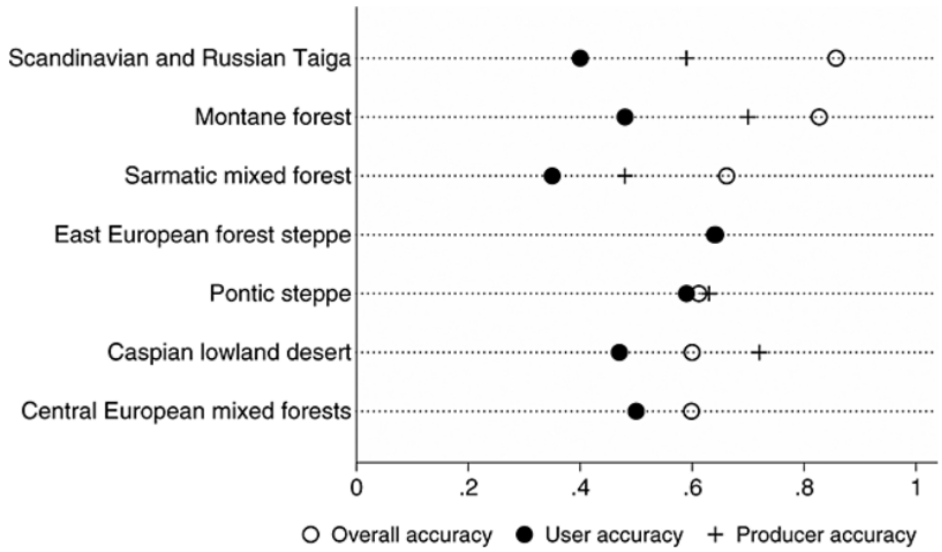

Figure II-5: Variations in accuracies among ecoregions.

Cropland abandonment

Between 1990 and 2009, 27.2 Mha of cropland was abandoned in European Russia, a decrease of 39%. In Ukraine, 3.2 Mha (8%) was abandoned between 1990 and 2008, and in Belarus, 0.6 Mha (9%) was abandoned between 1990 and 2003. Cropland abandonment since 1990 followed distinct patterns in different ecoregions, and the highest declines were recorded in the Scandinavian and Russian Taiga (3.5 Mha or 53%), and in the Sarmatic mixed forest ecoregion (5.7 Mha or 47%). More than 8 Mha of cropland was abandoned in the Pontic steppe after 1990. The abandonment rates were considerably lower in the central European mixed forest ecoregion, at 15%, the Pontic steppe zone, at 18%, and the east European forest steppe, at 28% (Figure II–4).

Clusters of cropland abandonment were concentrated in the central northern part of European Russia, where the agricultural suitability is relatively low, while less abandonment occurred in Ukraine and Belarus (Figure II–3, right). Massive cropland abandonment is also evident in the southern regions of European Russia, along a northwest-southeast precipitation gradient, with a spatial concentration in the dry Pontic steppe region at the border with Kazakhstan. Cropland coverage remained relatively stable in the central and southern regions of European Russia, which enjoy favorable soil and climatic properties.

Our annual cropland maps permit calculation of the time since abandonment. Almost 70% of cropland abandonment occurred within the first 10 years of the transition from a state command to a market-driven economy. After approximately 2000, cropland abandonment slowed significantly in Ukraine. This pattern was mirrored at the ecoregion level, namely, in the Pontic steppe, the east European forest steppe, and the central European mixed forest ecoregions (Figure II–4). Re-cultivation of abandoned cropland has been taking place in the Pontic steppe since approximately 2003, in the mixed forest ecoregion since 2006, and in the forest steppe since 2007. In contrast, cropland abandonment has continued unabated in the montane forest ecoregion.

Carbon sequestration

The LPJmL simulations showed that cropland abandonment in the study region led to a small carbon source over abandoned agricultural areas during the first years of the study period, as a consequence of low plant productivity and continuing carbon emissions from former cropland soils (Figure II–6). The model results suggest that early successional vegetation was established after approximately seven to eight years, when growing productivity started to influence the regional carbon balance with increasing rates of carbon sequestration. A net carbon sink developed in subsequent years, predominantly driven by rising levels of soil carbon sequestration due to high belowground productivity and turnover of grasses (Figure II–6).

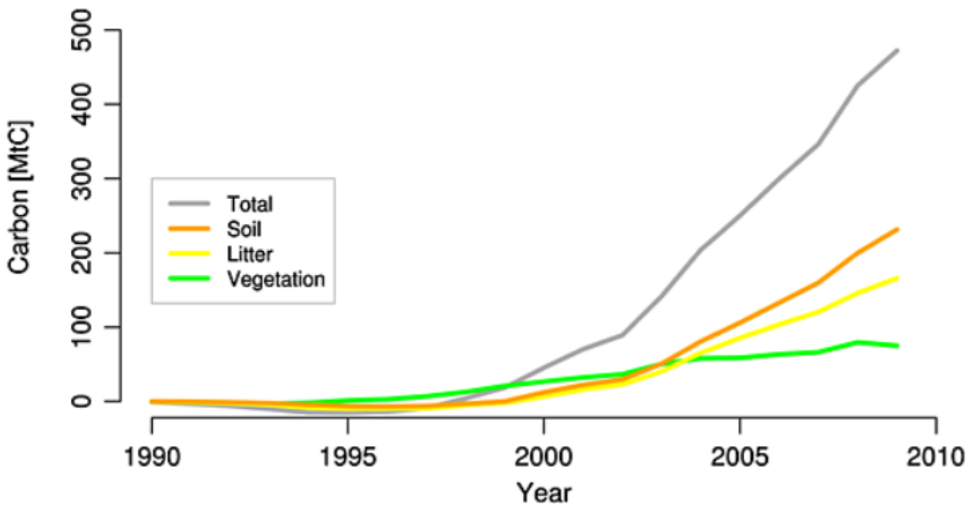

Figure II-6: Total carbon sequestration in vegetation and soils due to cropland abandonment in European Russia and Ukraine between 1990 and 2009. Note that Belarus is excluded because of missing data for cultivated area statistics. Cropland abandonment area and associated carbon sequestration are negligible in Belarus.

The total carbon sequestration due to cropland abandonment for the entire study region was estimated by LPJmL as 470 TgC for the 1991–2009 period, with an average sequestration rate of 70 gC/m^2/yr. The 2009 carbon sequestration rates varied between 50 and 80 TgC/yr across the study area, which is equivalent to 35% of the recent sink documented for the forests of European Russia (Pan et al. 2011). The largest amount of postabandonment carbon accumulation occurred in the western and central parts of the study area (Figure II–7), similar to the results from Vuichard et al. (2008), where cropland abandonment occurred early and extensively in the 1990s and climatic conditions foster higher plant productivity than in the east of the study region. Natural ecosystems in these areas include mixed forests and forest steppes, whereas steppe vegetation is the natural vegetation in the southeastern parts of our study region.

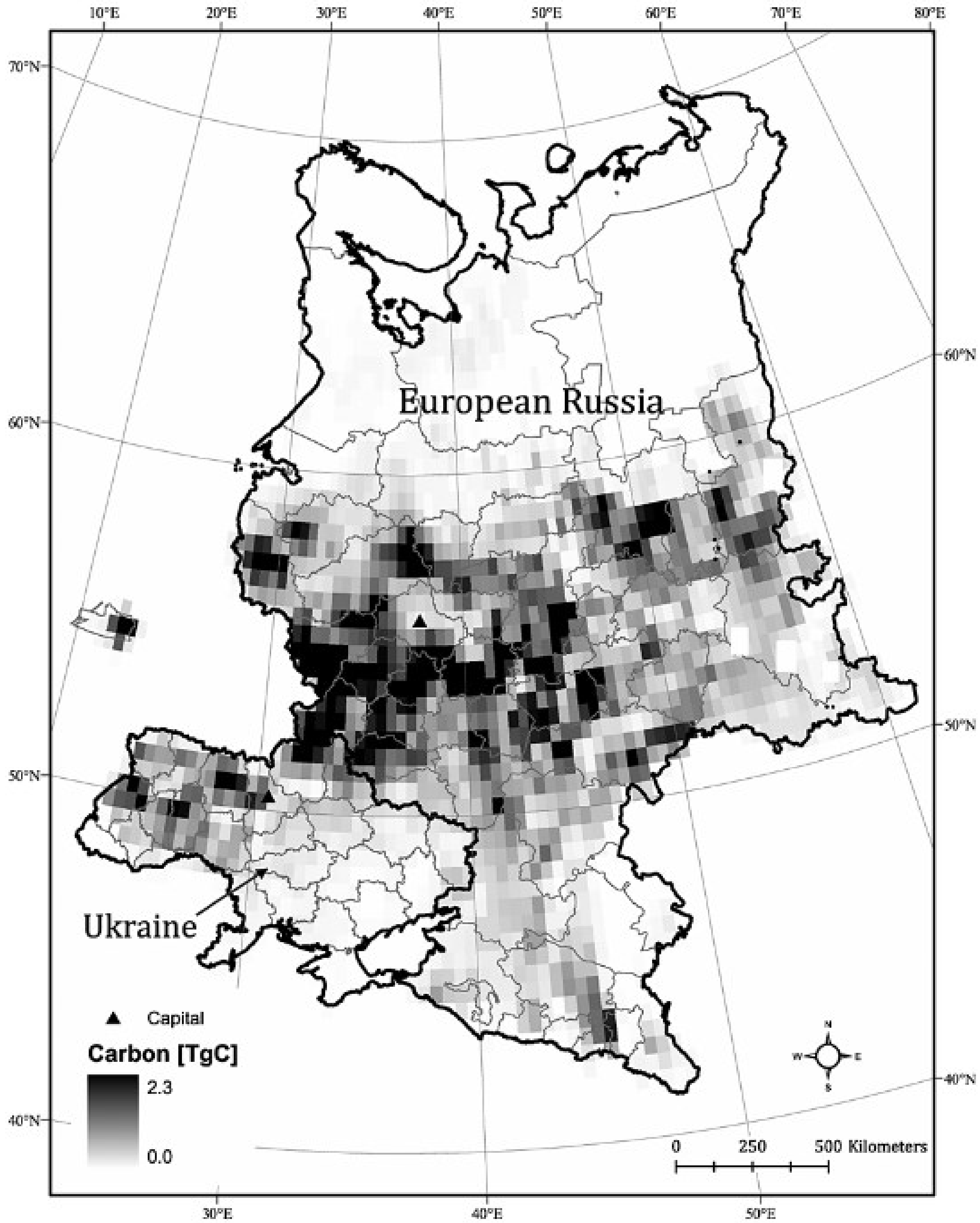

Figure II-7: Spatial distribution of total carbon storage on abandoned cropland between 1990 and 2009. *Note* that Belarus is excluded because of missing data for cultivated area statistics. Cropland abandonment area and associated carbon sequestration are negligible in Belarus.

Existing cropland maps for Russia, Ukraine, and Belarus are highly uncertain, mainly because they rely on unreliable and outdated agricultural statistics (Ioffe and Nefedova 2004; Ramankutty et al. 2008). This is a major obstacle to assessing cropland abandonment in the FSU, and thus to identifying the potential of idle cropland to improve global food production (Lambin 2012). Likewise, inaccurate cropland maps impair the assessment of carbon trade-offs of re-cultivating abandoned croplands.

We developed a spatial allocation model to produce maps of cropland and cropland abandonment in European Russia, Ukraine, and Belarus. The products are available for download at *http://www.iamo.de/lsc/downloads*. Our model allocates time series of agricultural statistics based on geophysical features and accessibility. Our overall accuracy is 65%, which is relatively high if compared to the overall accuracies of recent land cover maps produced by remote sensing alone for the same region (Alcantara et al. 2013; Gong et al. 2012). This is partly because other and more complex classes were mapped (for example, Alcantara et al. 2013) captured agricultural abandonment), but also due to the difficulty to accurately map land cover/use change using remote sensing.

We utilized the best available agricultural statistics for sown areas, which are correlated with fine-scale remotely sensed land cover data (Prishchepov et al. 2012). These statistics suggest that European Russia contained 50.96 Mha of cropland in 2009. This is 36.63 Mha, or 42%, less than the estimates of cropland cover in the region suggested by Ramankutty et al. (2008), which were based on national statistics from 1993 (Table II-1). Likewise, the sown area statistics utilized in this work are 3.09 Mha (9%) lower for Ukraine and 0.6 Mha (10%) lower for Belarus. The lower area differences for Ukraine and Belarus are due to the less substantial decline of cropland after the collapse of the Soviet Union in these countries. Similar overestimations of contemporary croplands in European Russia, Ukraine, and Belarus exist in other available cropland maps (Table II-1). Because of these overestimations, cropland abandonment following the breakup of the Soviet Union has been grossly underestimated, particularly in European Russia. For example, Campbell et al. (2008) derived estimates of agricultural land abandonment up to 2000 from the History Database of the Global Environment 3.0 (HYDE 3.0, Klein Goldewijk 2001) and from the Center for Sustainability and the Global Environment (SAGE) cropland map (Ramankutty and Foley 1999), both of which rely on FAO statistics that fail to capture the extent of post-Soviet cropland abandonment.

Errors in our cropland maps can originate from our simplifying approach to allocate annual sown area statistics on the cropland mask solely based on a suitability map that relies on the land rent theories of Ricardo and von Thünen. Moreover, the cropland suitability map may contain inaccuracies due to imperfect input data and limitations of the spatial regression model. Maybe more importantly, the location of sown areas also depends on factors not considered here, such as institutional support for agriculture (Wandel et al. 2011), farm productivity (Bokusheva and Hockmann 2006), path dependency in agricultural production, and changes in rural demography (Ioffe and Nefedova 2004). Improvements in accuracy of cropland maps are possible with finer agricultural inventory statistics, particularly on yields and sown areas, and more precise geophysical data. In addition, a more detailed and spatially explicit understanding of the drivers of cropland change can help improving the allocation rules.

Our simulation results highlight the nonlinear change in carbon sequestration rates on former croplands after the beginning of postsocialist agricultural land abandonment, which corresponds to field measurements from the region (Kurganova et al. 2013). Net carbon uptake in vegetation and soils accelerated particularly after 2000 (i.e., 10 years after the collapse of the Soviet Union) as a consequence of two concurrent processes. First, vegetation regrowth on former croplands passes through a transition from carbon source to sink during the first 5–10 years after abandonment, which is typical for boreal forest succession (Goulden et al. 2011). Similarly, field investigations in temperate Russia have demonstrated that former croplands provide stable sinks four to five years after abandonment (Kurganova et al. 2013). Second, cropland abandonment was not a singular event but evolved gradually, especially in the first 10 years after the collapse of the Soviet Union. During this period, carbon sources in newly abandoned areas partly counterbalanced the emerging carbon sinks in areas in later stages of succession. This effect diminished over time with decreasing cropland abandonment rates. A major conclusion from our work is thus that after the transitional period, during the early years of natural vegetation regrowth, carbon uptake and thus potential emissions from re-cultivating abandoned areas increase significantly each year.

Carbon sequestration occurs predominantly in soil carbon stocks, typically in systems in which early succession is dominated by C3 grass species with high belowground productivity. Establishment and regrowth of tree species are relatively slow under the prevailing climatic conditions, under which evergreen trees will ultimately determine species composition in natural vegetation during later succession stages, beyond the temporal scope of this study (Goulden et al. 2011). Overall, our simulations showed that the carbon sequestration rate on abandoned lands by 2009 was still approximately 50% less than for the mature natural vegetation that would ultimately develop on these lands. Carbon sequestration will therefore continue for many years until it decreases again in old-growth boreal forests (Luyssaert et al. 2008). Re-cultivating all abandoned areas could release more than 400 TgC into the atmosphere and would result in foregone future carbon sinks in natural vegetation. Re-cultivation would thus not only threaten to release the carbon stored since abandonment but would also lead to substantially less carbon sequestration by preventing current systems from reaching climax vegetation. Both carbon stored at present and foregone future carbon sequestration should hence be accounted for, particularly if re-cultivation would focus on bioenergy production for climate mitigation purposes (Vuichard et al. 2009).

We have developed the first high-resolution time series of cropland and cropland abandonment maps for this agriculturally important region. These maps show that cropland abandonment has been severely underestimated in the Soviet Union and that patterns of abandonment were heterogeneous across the region and during the period after 1990. Using these maps in a dynamic vegetation model reveals a nonlinear relationship between the time since cropland was abandoned and the amount of carbon sequestered. We also showed that abandonment led to substantial carbon sequestration and that re-cultivation of the currently abandoned lands would be associated with high carbon emissions. Our spatially and temporally explicit cropland abandonment data therefore improve the estimation of carbon costs involved in reclaiming abandoned croplands and will help to identify trade-offs involved in increasing agricultural production in this globally important agricultural region.

Acknowledgments

Comments by K. Hahlbrock, two anonymous reviewers, and the editor greatly improve this manuscript. We benefited from discussions with O. Kalinina, J. Sheets, U. Franko, M. Baumann, P. Meyfroidt, I. Kurganova, N. Vuichard, and D. Lyuri. We also thank J. Krishna Thakur and G. Hongjiang for interpreting the Google Earth imagery and T. Labs and N. Yermakova for their support in compiling the data. We gratefully acknowledge financial support by the Leibniz Association's "*Pakt für*

Forschung" (projects Bioenergy Planet and EPIKUR), the German Federal Ministry of Education and Research (BMBF) (Code01LL0901A, projects KULUNDA and GLUES), the project funded by the German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU, project: Nachhaltige europäische Biomethanstrategie, FKZ 03KB024); the European Commission (VOLANTE FP7-ENV-2010-265104 and POLFREE FP7-ENV-2012-632), and the Einstein Foundation Berlin.

Supporting information

Text S II-1: Cropland Mask

To generate the cropland mask, we overlaid three global land cover products, namely, MODIS MOD12Q1 (Friedl et al. 2002), GLC-2000 (Bartholomé and Belward 2005), and GlobCover (Bicheron et al. 2008). The data are available for approximately the year 2000 (GLC2000, MODIS) and 2005 (GlobCover). A detailed description of these datasets is provided in Ramankutty et al. (2008) and Giri et al. (2005) for MODIS and GLC2000 and by Fritz et al. (2011) for MODIS, GLC2000, and GlobCover.

It is probable that the number of correctly classified observations will increase if two or more products contain a similar land cover category. We applied a statistical fusion procedure similar to that used by Ramankutty et al. (2008) to identify reliable cropland observations for the study area. To do this, we first merged all categories of the three global land cover products. This merger produced 3,615 land cover class combinations, of which we excluded 1,102 combinations without any classes related to cropland. We then kept only the class combinations that are present in all 86 provinces of the study area, to maintain a sufficient number of observations and to obtain robust parameter estimates. This approach reduced the number of cropland-related classes to 125. We then summed these classes for each province to compare them with the provincial-level cultivated area statistics. We utilized the statistics for 1990 because 1990 had the largest area under cultivation in 84 of the 86 (97%) provinces in European Russia, Ukraine, and Belarus. Hence, the proportion of area under cultivation in 1990 was the response variable in a multiple linear regression model, and the proportions of land cover class combinations were the predictors. We used linear stepwise regression with backward selection ($p<0.1$) to estimate the 125 coefficients, one per cropland-related class, at the provincial level.

Predictions of cropland-related class combinations were obtained by summing the total area of all significant combinations of land cover classes. The predicted values and reported cultivated area statistics were highly correlated

(Pearson R^2=0.89), suggesting that the cropland-related class combinations successfully captured the croplands of 1990. To ensure a complete allocation of the cultivated area statistics for all years from 1990 to 2009 and all administrative units, we added additional land cover class combinations. We implemented this by gradually increasing the *p*-values in the regressions until the estimated cropland area exceeded the reported cultivated area statistics for all regions and all years by a threshold value of 20%, which resulted in a cropland mask with low errors of omission. The introduction of the 20% threshold has little effect on the final cropland maps because the cropland mask merely captures the potential locations of cropland, whereas the allocation of the cultivated area statistics is based solely on cropland suitability.

Text S II-2: Hydrothermal Coefficient

We omitted observations with climate-driven anomalies that were mainly caused by droughts during the growing season. To identify drought years, we calculated the hydrothermal coefficient (HTC) during the summer seasons at the district level for all the years in which grain yields were reported. The HTC is the total precipitation in the growing season, multiplied by 10 and divided by the sum of the daily average temperatures within the growing period (Dronin and Kirilenko 2008). The growing period is defined as the period with daily temperatures above 10°C. The HTC typically ranges between 0.4 and 2, and an HTC below 0.7 indicates drought conditions during the growing season (Dronin and Kirilenko 2008). To estimate the yearly HTC, we used daily gridded precipitation and maximum temperature data at a half-degree spatial resolution (Schuol and Abbaspour 2007), and we computed the area-weighted mean at the district level. The grain yields in non-drought years (HTC above 0.7) were then averaged to obtain an estimate of habitual grain yields.

Text S II-3: Soil Quality Map

We used principal component analysis to obtain uncorrelated linear combinations of the soil parameters from the Harmonized World Soil Database (HWSD). We weighted the estimated principal components according to the method described by Andrews et al. (2002) and calculated the medians of all principal soil components at the district level. We then plotted these medians against average grain yields to allow identification of the type of functional relationship. Finally, we assigned these functions to principal components and translated these into a linear index that indicates the soil quality. Yield statistics for other crops were unavailable at the district level, but grain production covers by far the largest area in the study region and therefore reflects the main spatial pattern of soil quality.

Figures supporting information

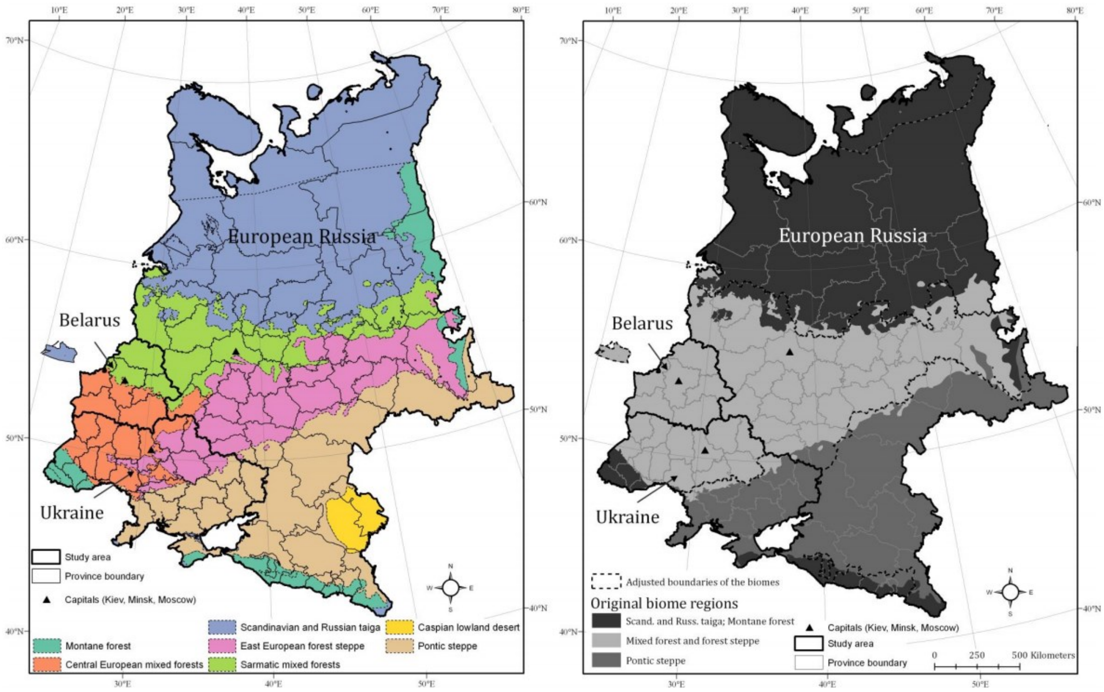

Figure S II-1: Ecoregions (left) and biomes (right). Note that we adjusted biome boundaries (available at *http://www.worldwildlife.org/science/ecoregions/item1847.html*) to provincial boundaries.

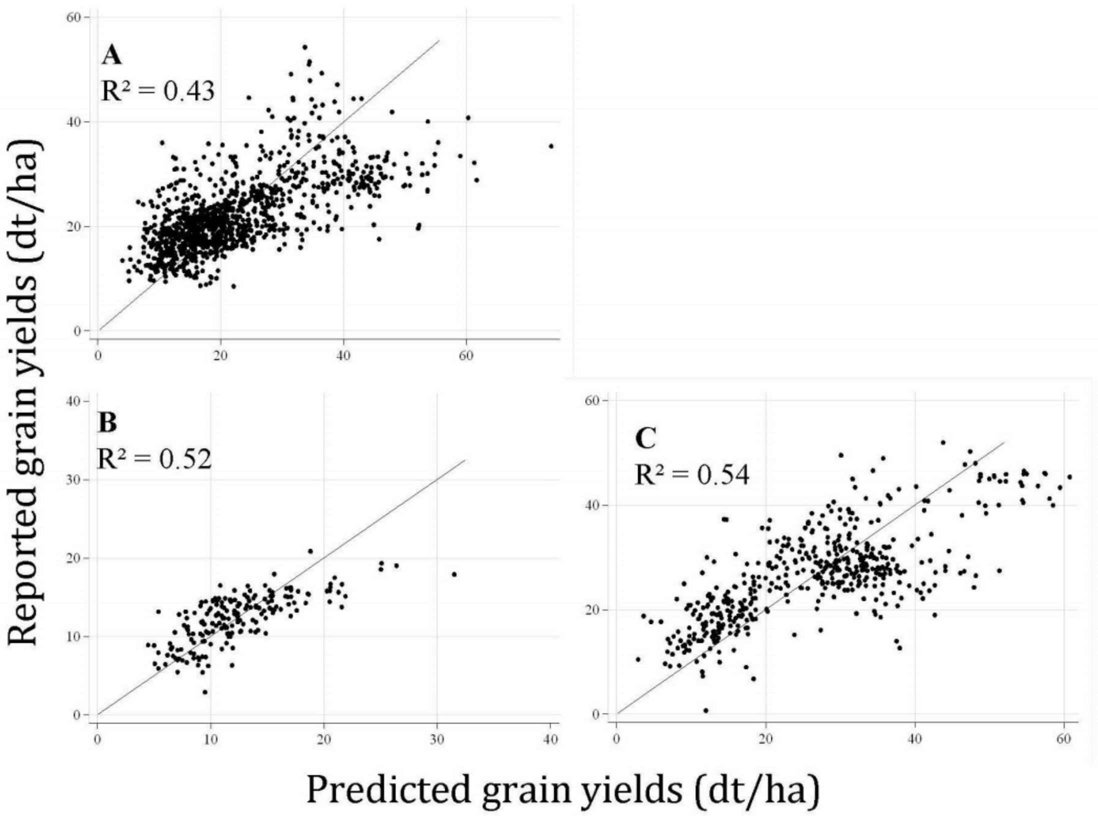

Figure S II-2: Correlation of reported and predicted grain yields for A) Mixed forest and forest steppe, B) Scandinavian and Russian taiga, and C) Pontic steppe.

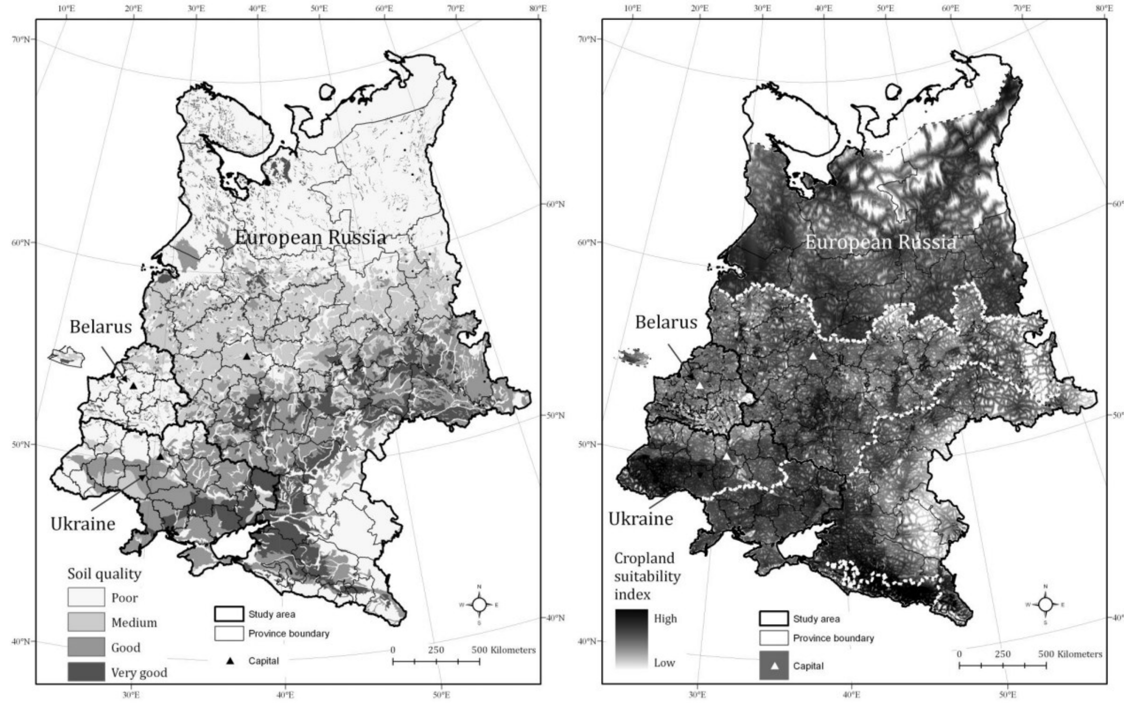

Figure S II-3: Soil quality (left) and cropland suitability (right). Note that the continuous soil quality index (left) is classified into quartiles. The map shows high soil quality in the Chernozem belt in European Russia and Ukraine. The cropland suitability index (right) was estimated for each of the three biomes. The dashed white line indicates the adjusted biome boundaries.

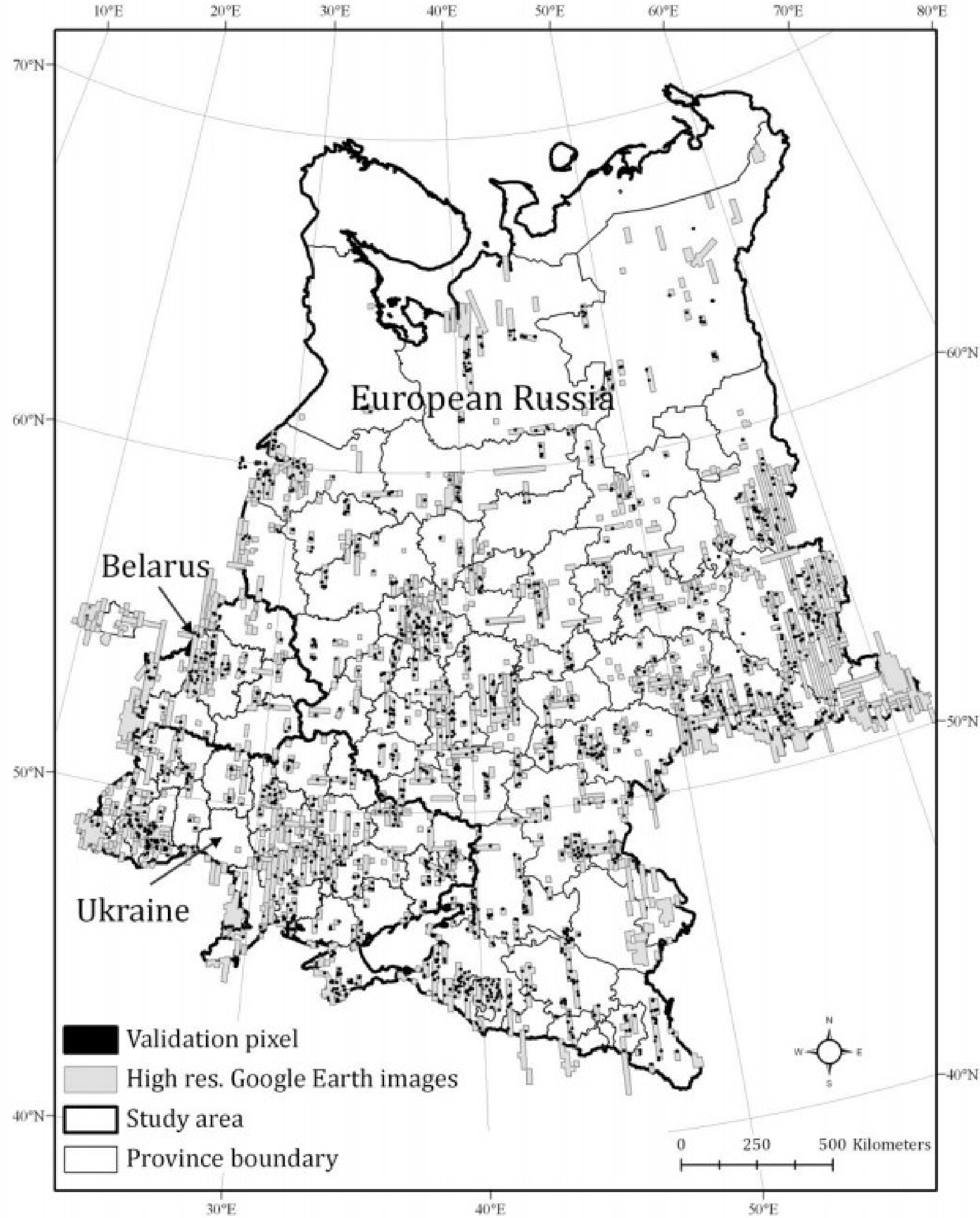

Figure S II-4: Locations of the high-resolution QuickBird and IKONOS images from Google Earth and validation pixels.

Tables Supporting information:

Table S II-1: Sources of agricultural inventory data.

	Unit	Years	Source
Sown area			
Russia	Province	1940-2009	ROSSTAT (2010)
Ukraine	Province	1940-2008	UKRSTAT (2009)
Belarus	Province	1990-2003	BELSTAT (2004)
Grain yield			
Russia	District	1990-2009	*www.radford.edu/~agrorus/index.htm*
Ukraine	District	1990, 2005-2009	Association Ukrainian Agribusiness Club
Belarus	District	1995, 2000, 2002, 2003	BELSTAT (2004)

Table S II-2: Sources of abandonment estimates.

Source	Area (Mha)	Period/Year	Label
Ioffe et al. (2004)	20.0	2004	Abandoned arable land
Romanovskaya (2006)	21.6	1992-2002	Cropland abandonment
Klyuev (2001)	29.0	1990-1999	Cropland abandonment
Kurganova et al. (2010)	30.2	1990-2005	Cropland abandonment
Ivanov (2004)	32.0	1985-2003	Cropland abandonment
Pankova and Novikova (2000)	34.0	1990-1995	Cropland abandonment
Lyuri et al. (2010)	48.0	1990-2007	Abandoned arable land

Table S II-3: Descriptive statistics and results of the three different regression models for grain yields.

Biome	Variable	Mean	SD	OLS	Spatial error regression	Spatial lag regression
Mixed forest and forest steppe	Observations			1,060	1,060	1,060
	Grain yield	22.1	10.7			Dependent variable
	Precipitation	50.7	12.5	0.34***	0.04	0.069***
	Travel time	115.4	55.7	-0.03***	-0.001	-0.0079**
	Soil quality	169.3	13.5	0.15***	0.06***	0.04***
	Constant			-16.96***	10.420**	-6.800**
	Spatial lag					0.81***
	Pseudo R2			0.19	0.75	0.73
	Log-likelihood			-3,928.0	-3,402.1	-3,419.6
Scandinavian and Russian taiga	Observations			187	187	187
	Grain yield	12.3	4.3			Dependent variable
	Precipitation	47.6	2.8	-0.47***	-0.2614**	-0.20***
	Travel time	166.3	81.0	-0.02***	-0.0238***	-0.01***
	Soil quality	166.9	7.4	0.08***	0.03	0.04**
	Constant			25.03***	23.48***	11.65*
	Spatial lag					0.51***
	Pseudo R2			0.51	0.62	0.64

	Log-likelihood			-475.6	-457.4	-452.0
	Observations			480	480	480
Pontic steppe	Grain yield	26.7	12.0			Dependent variable
	Precipitation	45.3	16.8	0.33***	0.0526	0.05***
	Travel time	126.7	71.1	-0.06***	-0.001**	-0.01***
	Soil quality	180.1	8.2	0.3237***	0.12***	0.08***
	Constant			-38.15***	2.41	-11.78**
	Spatial lag					0.86***
	Pseudo R2			0.37	0.87	0.87
	Log-likelihood			-1,760.6	-1,442.8	-1,434.8

Source: Own calculations; standard errors, z-statistics, and p-values are suppressed for the sake of brevity, but can be obtained from the authors upon request. *p<0.10, ** p<0.05, *** p<0.01.

Table S II-4: Confusion matrix.

		Reference data (Google Earth)			
		Non-cropland	Cropland	Sum	User's accuracy
Cropland map 2003	Non-cropland	622	271	893	0.70
	Cropland	254	325	579	0.56
	Sum	876	596	1,472	
	Producer's accuracy	0.71	0.55		
	Overall accuracy	0.65			

Chapter III Quantifying yield gaps in wheat production in Russia

Environmental Research Letters, Vol. 9 (2014), No. 8.

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Abstract

Crop yields must increase substantially to meet the increasing demands for agricultural products. Crop yield increases are particularly important for Russia because low crop yields prevail across Russia's widespread and fertile land resources. However, reliable data are lacking regarding the spatial distribution of potential yields in Russia, which can be used to determine yield gaps. We used a crop growth model to determine the yield potentials and yield gaps of winter and spring wheat at the provincial level across European Russia. We modeled the annual yield potentials from 1995 to 2006 with optimal nitrogen supplies for both rainfed and irrigated conditions. Overall, the results suggest yield gaps of 1.51–2.10 t ha^{-1}, or 44–52% of the yield potential under rainfed conditions. Under irrigated conditions, yield gaps of 3.14–3.30 t ha^{-1}, or 62–63% of the yield potential, were observed. However, recurring droughts cause large fluctuations in yield potentials under rainfed conditions, even when the nitrogen supply is optimal, particularly in the highly fertile black soil areas of southern European Russia. The highest yield gaps (up to 4 t ha^{-1}) under irrigated conditions were detected in the steppe areas in southeastern European Russia along the border of Kazakhstan. Improving the nutrient and water supply and using crop breeds that are adapted to the frequent drought conditions are important for reducing yield gaps in European Russia. Our regional assessment helps inform policy makers and agricultural investors and prioritize research that aims to increase crop production in this important region for global agricultural markets.

Introduction

Global agricultural production must increase substantially to satisfy the growing demand for agricultural products that has resulted from population growth, higher-calorie diets, and the use of land-based resources for biofuel production (Godfray et al. 2010). Two options are available for increasing agricultural production. The first option is to increase the area of cultivated land. However, further expansion carries considerable environmental costs (Foley et al. 2005; Lambin and Meyfroidt 2011). The second option is to enhance productivity on existing agricultural lands. Higher yields may prevent the conversion of non-agricultural lands into agricultural lands because more output would be obtained from the existing agricultural land (Green et al. 2005; Rudel et al. 2009). Thus, increased crop yields will be important for satisfying the growing demands for food, feed, fuel, and fiber while minimizing adverse environmental effects (Mueller et al. 2012).

However, current yield improvements may occur too slowly to meet the increasing demands for agricultural products (Ray et al. 2013). Moreover, the potential for improving crop yields varies widely around the world, and large yield gaps (i.e., differences between potential and actual yields) are common. For example, the yield gaps are generally large in developing and transitional countries, in which substantial limitations in agricultural management, infrastructure, education, and agricultural policies often impede increases in land productivity (Neumann et al. 2010; Tilman et al. 2011). Conversely, many developed countries have already crop yields that are close to its yield potentials, and the costs of additional yield increases could outweigh the economic benefits (Lobell et al. 2009). Better data and knowledge regarding the sizes, spatial distributions, and determinants of yield gaps could be used to target policies and management practices that increase crop productivity.

Crop growth models can estimate potential yields by simulating the optimal management conditions that ensure crop growth under conditions with no stress from weeds, pests, and diseases and with sufficient available nutrient content and water (Evans and Fischer 1999). Under such optimal management conditions, the yield potential becomes a function of the prevailing climate, biophysical conditions, and cultivars. Consequently, the effects of crop management on yields can be tested (Lobell et al. 2009).

Crop growth models can accurately estimate yield potentials at small spatial scales (i.e., the plot and field scales) if sufficient information is available for model calibration (Asseng et al. 2013). Unfortunately, few small-scale estimates of yield potentials exist, and many important agricultural areas are underrepresented. The extrapolation of small-scale yield potentials to larger regions requires sufficient, intercomparable, and consistent estimates that capture the interactions between the biophysical conditions, cultivar choice, and crop management for distinct biophysical zones (van Ittersum et al. 2013). A number of studies have aimed to fill this gap by using crop growth models to estimate the yield potential of large areas, including sub-national regions, countries, and the world (Boogaard et al. 2013; Liu et al. 2007; Nelson et al. 2010; Rosegrant et al. 2014). Large-scale applications rely on consistent data and methods and can help identify yield gap hotspots. However, the results from large-scale application typically have greater uncertainty.

The uncertainties of large-scale models can result from the generalizations that are required when using conceptual models. This uncertainty may result from coarse or inaccurate input data (for example, weather and agricultural management, Folberth et al. 2012; van Bussel et al. 2011; Van Wart et al. 2013b). In addition, parameter uncertainty can result from non-unique parameters during inverse modeling (Abbaspour et al. 2007). For example, parameter uncertainty may originate from the estimated soil-physical and crop phenological parameters for which measured data are typically not available at large scales. Consequently, the calibration of large-scale crop growth models must include a thorough uncertainty assessment, particularly if the results will be used to inform decision makers (Folberth et al. 2012; Rotter et al. 2011).

To our knowledge, model-based yield gap estimates that cover long periods are not available for large areas of Russia. This lack of information is unfortunate because Russia plays an important role in global agricultural markets (Liefert et al. 2010; OECD-FAO 2010). Russia is particularly interesting because the collapse of the Soviet Union triggered a considerable decline in crop yields (FAO 2014). Furthermore, wheat yields have remained well below the yields that are achieved under comparable natural conditions in other countries (Licker et al. 2010). This difference suggests that yield increases could boost Russian wheat exports and the global wheat supply.

Overall, our goal was to estimate the yield gaps of winter and spring wheat (Triticum aestivum L.) at the provincial level in European Russia. The European region of Russia represents 63% of the total wheat cultivation region in Russia and accounts for 75% of Russia's wheat production (ROSSTAT 2014). We calibrated a crop growth model for European Russia to simulate wheat yields between 1995 and 2006 and conducted a quantitative uncertainty assessment of the yield simulations. The results from this assessment allowed us to determine the wheat yield potentials and yield gaps under both rainfed and irrigated conditions. We used the soil and water assessment tool (SWAT, Arnold et al. 1998), which has been widely used to assess the impacts of agricultural management and climate on crop yields and agricultural production (Gassman et al. 2007; Sun and Ren 2014). The SWAT model includes sophisticated calibration-validation options, a sensitivity analysis, and an uncertainty assessment and is well suited for simulating plant growth across large areas.

Materials and methods

Study area

European Russia stretches across approximately four million km^2 (Figure III–1, A). In 2009, croplands covered 55.6 million hectares (Mha) of this region, or 14% of the total area. In addition, 20.6 Mha (37%) of this area were used for growing wheat (ROSSTAT 2014). European Russia has access to the Black Sea, which has important grain terminals for exporting production (Wegren 2012). The cropland distribution follows soil fertility and climatic gradients. Infertile podsolic soils with minimum solar radiation, short growing periods, and an average yearly precipitation of 500–700 mm dominate the northern region of European Russia (Figure III–1, B). Low nitrogen (N) fertilizer inputs and small cultivated area in the north result in low crop yields and small crop production (Figure III–1, C and D). In contrast, higher N inputs, the fertile soils, such as Chernozems (black earth soils), longer growing periods, and a greater cultivation area in the southern and southwestern regions result in higher crop yields and a higher crop production.

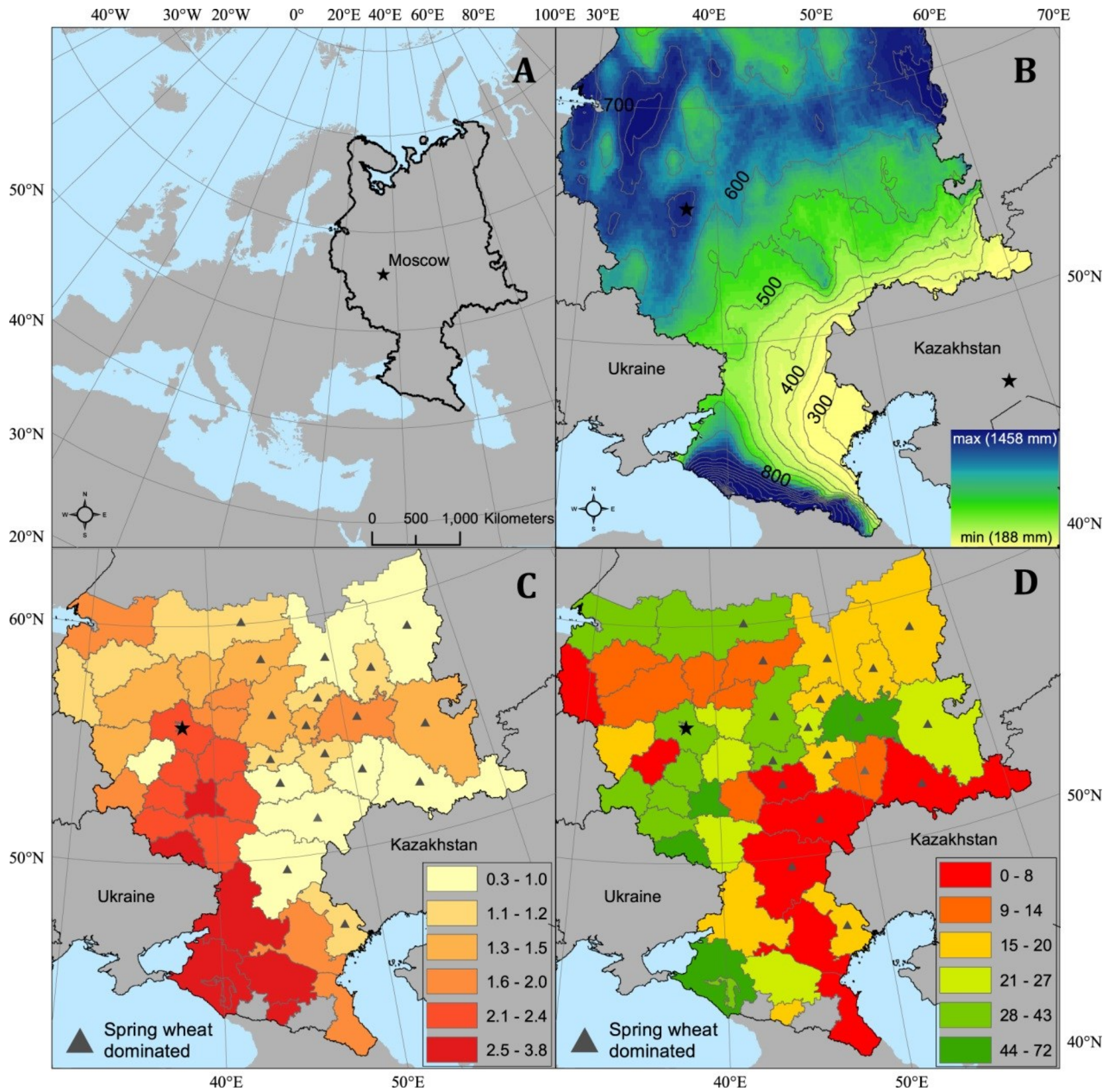


Figure III-1: Study region (A); average annual precipitation (mm) (B); average wheat yields (t ha^{-1}, 1991–2012) (C); average N fertilizer use (kg/ha, 1991–2012) (D). Data sources: Climatic Research Unit (CRU, TS 1.0 and 2.0, *http://www.cru.uea.ac.uk/cru/data/hrg.htm*) (B); ROSSTAT (2014) (C) and (D).

However, stable anticyclone circulation with dry air during the summer results in recurrent and severe droughts in southern European Russia (Dronin and Kirilenko 2008). During the 20th century, major droughts occurred in southern European Russia at least 27 times (Meshcherskaya and Blazhevich 1997). Thus, on average, every fourth year was affected by limited precipitation, which results in frequent yield declines and production shortfalls in the southern breadbaskets. Widespread irrigation networks for mitigating the impacts of drought on yields were built during the Soviet era. However, these networks have fallen into disrepair since the collapse of the Soviet Union (USDA 2013). Continental, dry weather conditions characterize the southeastern portions of European Russia (Figure III–1, B) where spring wheat dominates the cropping patterns. In southeastern portions of European Russia, irrigation practices are rare and N application rates are generally low, particularly near the Kazakhstan boarder (Figure III–1, D).

Since the collapse of the Soviet Union, Russia has transitioned from being a net importer of wheat (17.59 million tons (Mt) in 1992) to one of the top five net exporting countries of wheat (16.82 Mt in 2009, FAO 2014), mainly because the collapse of the Russian livestock sector reduced the domestic demand for fodder crops (Lioubimtseva and Henebry 2012; ROSSTAT 2014). However, the volatile climate conditions have caused large annual fluctuations in wheat yields, as observed in 2010 when Russia only exported 11.85 Mt of wheat (FAO 2014). The global importance of Russian wheat production is mainly attributed to its large area of wheat cultivation. Although the total cropland decreased by 35% or 41.1 Mha from 1990 to 2011 (from 117.7 to 76.6 Mha), mainly because of the contraction of fodder production, the wheat cultivation area remained fairly stable during this period (from 24.2 Mha to 25.5 Mha, ROSSTAT 2014). The average area harvested for wheat was 24.8 Mha between 2008 and 2011, which was second only to India (28.3 Mha, FAO 2014).

Between 2008 and 2011, the average wheat yield in Russia was only 2.2 t ha^{-1}. In contrast, Germany and France achieved 7.6 and 7.0 t ha^{-1}, respectively, during this period (FAO 2014). The average winter wheat yields in Russia decreased from 1.93 t ha^{-1}between 1990 and 1992 to 1.49 t ha^{-1} between 1994 and 1996 after the collapse of the Soviet Union, which corresponded to a decrease of 23%. In the early 1990s, the decline in winter wheat yields was driven by the collapse of state support for agriculture and the liberalization of markets, which greatly reduced the ratio of the agricultural output prices to input prices and resulted in decreased input intensity (Rozelle and Swinnen 2004). Particularly, N fertilizer use declined from 88 kg ha^{-1} in 1990 to 17 kg ha^{-1}in 1995, which corresponded to a decrease of more than 80% (Figure III–2). The 23% decrease in wheat yields during the early 1990s was substantially lower than the 80% decrease in N fertilizer application because the fields were often over-fertilized at the end of the Soviet era, which resulted in diminishing N returns (Liefert et al. 2003). Moreover, the long-term effect from high fertilization during socialist times likely resulted in the diminished yield declines in the early 1990s (Gutser et al. 2005). The increasing wheat yields after 1998 partially resulted from better weather conditions, but also resulted from the recovery of the agricultural sector and the concurrent increase of the agricultural input intensity, particularly for N fertilizer (Figure III–2) and high-quality seeds (Liefert et al. 2010).

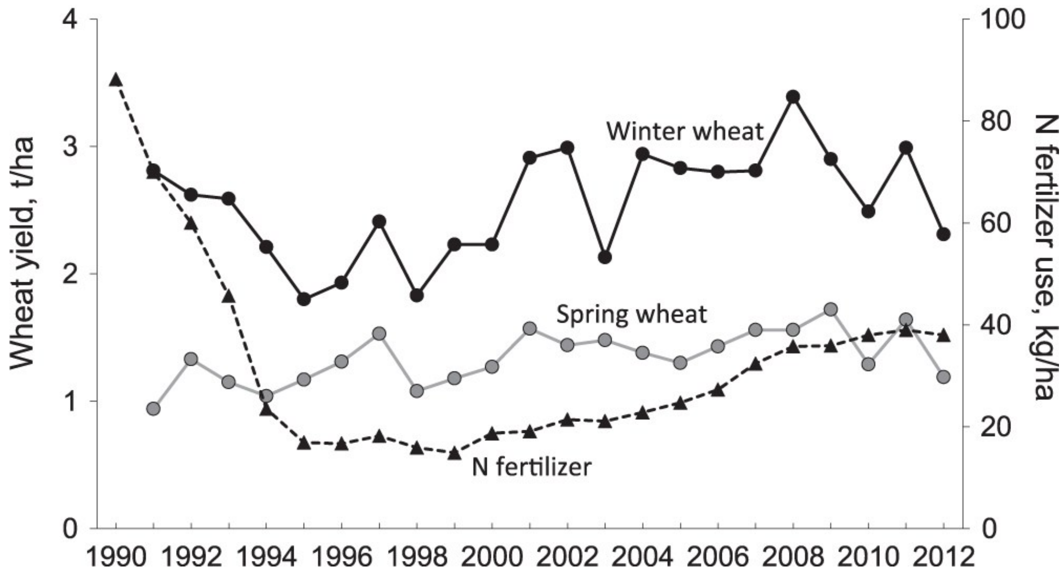


Figure III-2: Wheat yields and nitrogen fertilizer use in Russia. Data source: ROSSTAT (2014).

Crop growth model

We applied the SWAT model to simulate potential yields. The SWAT model is a process-based, spatially distributed model that operates on a daily time step (Arnold et al. 1998). SWAT has been used in various applications for quantifying the impacts of land management and climate on plant growth, yield, and hydrological parameters (Gassman et al. 2007). Spatial parameterization of the SWAT model was performed by delineating a watershed into sub-basins according to topography and into hydrologic response units (HRUs) according to soil and land-use characteristics. SWAT uses daily climate data, such as precipitation, the minimum and maximum temperatures, and solar radiation, from weather stations to simulate the plant water uptake, transpiration, vegetation phenology, soil and canopy evaporation, and other hydrological components daily. The provision of solar energy drives the vegetation phenology and biomass production.

Plant growth was simulated using the crop growth component of the SWAT model, which is a simplified version of the erosion productivity impact calculator (Williams et al. 1989). The EPIC computes the leaf area development, light interception, and biomass conversion in the absence of biotic and abiotic limitations.

The actual biomass growth is simulated by imposing stress during plant growth, including insufficient water supply, temperatures beyond the ideal crop-specific ranges, and N and phosphorus limitations. The amount of simulated aboveground biomass is converted to actual yield by multiplying it by a crop-specific harvest index that is inhibited by a water stress factor. The water stress is calculated as the ratio of actual to potential plant transpiration. According to heat unit theory, the EPIC assumes that all heat above a plant-specific base temperature accelerates plant growth and development until a temperature cut-off is reached (Neitsch et al. 2005). The crop growth component of the SWAT model can reproduce observed wheat yields in various geographical settings (Ashraf Vaghefi et al. 2014; Faramarzi et al. 2010; Sun and Ren 2014). We used the SWAT Calibration and Uncertainty Program (SWAT-CUP, Abbaspour et al. 2007) to calibrate, validate, and assess the uncertainties of the crop growth simulations.

Data

Global agricultural datasets, which include planting dates (Sacks et al. 2010), amounts of irrigation (Portmann et al. 2010), fertilizers inputs (FAO 2007), cropland extents (Ramankutty et al. 2008), and yields (Monfreda et al. 2008), have generally provided coarse and outdated information for Russia. Insufficient input data may inhibit the production of reliable yield potential estimates. Therefore, we obtained yearly data at the provincial level for winter and spring wheat yields between 1991 and 2006. In addition, N fertilizer inputs were obtained for 1993–2006 and the sowing areas of winter and spring wheat were obtained for 2006. These data were obtained from the official Russian agricultural inventories (ROSSTAT 2014). Because information regarding the dates of N fertilizer application was not available, we used the auto-fertilizer application function in the SWAT model. Auto-fertilization begins when N stress occurs in the plants. Data regarding the length of the growing season for wheat (from the date of planting to the date of harvesting) were obtained from the Rukhovich et al (2007), USDA (2013), and GOSSORT (2014).

To ensure that only the relevant wheat production systems were captured for the yield simulations, we selected 28 provinces with more than 25 000 ha under wheat cultivation in 2006, which corresponded to the most recent yield and input data. In 13 of these provinces, winter wheat dominated the cropping patterns in 2006.

Spring wheat dominated in 15 provinces. In each province, we selected the sub-basin with the largest cropland area as the HRU for the crop growth simulations (Figure III–3).

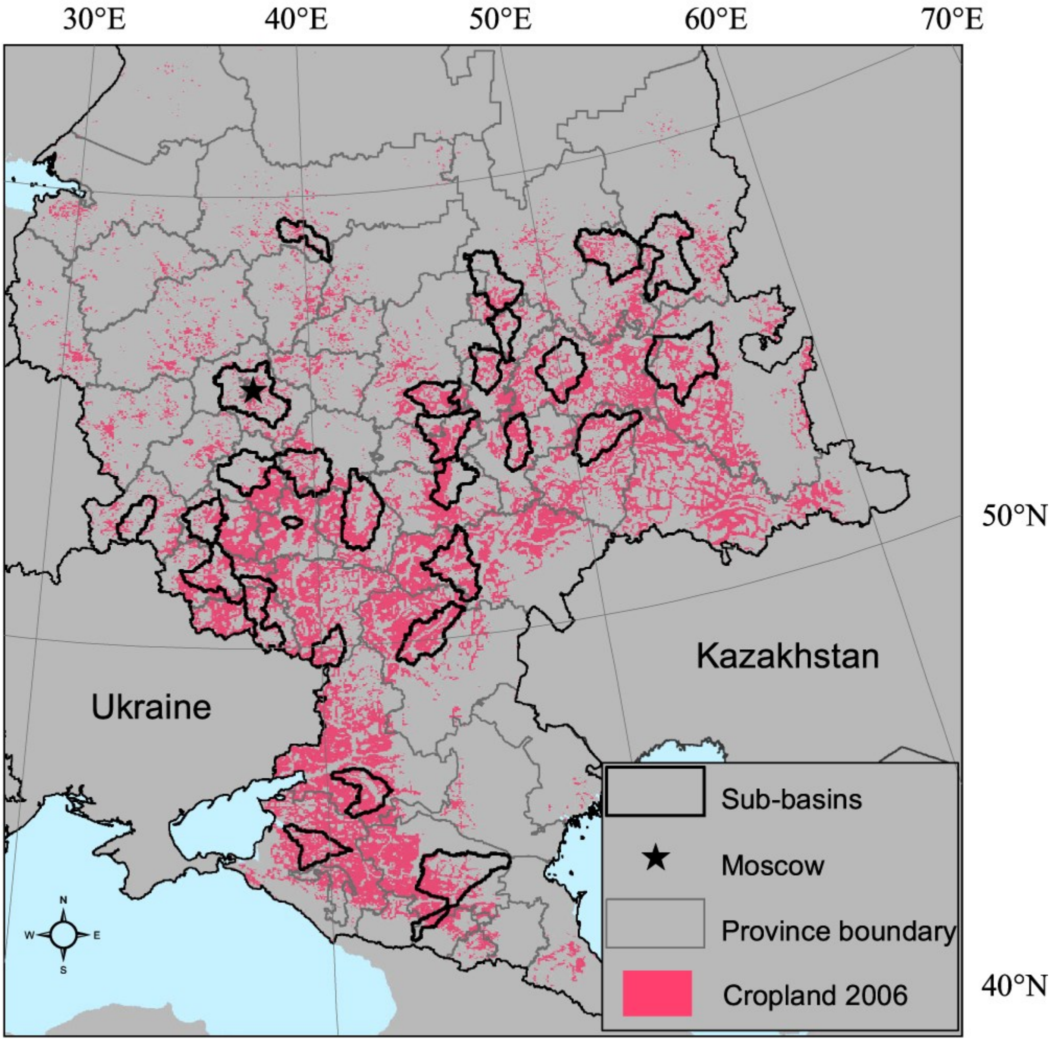


Figure III-3: Selected sub-basins.

We extracted soil parameters from the Harmonized World Soil Database, which is a raster database with a spatial resolution of 30 arcseconds that was assembled from regional and national updates of soil information (FAO et al. 2012). The climate data included monthly statistics for the total precipitation, average minimum and maximum temperatures, and the number of wet days per month (Climatic Research Unit (CRU), TS 1.0 and 2.0, *http://www.cru.uea.ac.uk/cru/data/hrg.htm*). Because consistent and daily data were not available from weather stations for our study area, we simulated the daily precipitation, temperature, and number of wet days per month using the monthly CRU statistics. For this simulation, a stochastic, semi-automated daily weather generator was used that generates data that well agree with the daily measured data (Schuol and Abbaspour 2007) and has been used in crop modeling (for example, Mekonnen and Hoekstra 2011). We used the GTOPO30 digital elevation model from the US Geological Survey to delineate 546 sub-basins to obtain a realistic representation of the hydrological and agricultural characteristics for implementation in the SWAT model. The cropland patterns within each sub-basin were characterized by using data from Schierhorn et al (2013), and the dominant soil, land use, and slope options in SWAT were used to determine the hydrological parameters of each sub-basin.

Data regarding the application of other nutrient inputs (phosphorus and potassium) and pesticides were not available. However, the sensitivity analysis in SWAT suggested that the crop yields in our study region were insensitive to crop rotations and phosphorus, potassium, and pesticide inputs. Similarly, field trials in the non-Chernozem regions of European Russia demonstrated that the sensitivities of wheat yields to phosphorus and potassium applications were negligible (Kolomiec 2007). To compare the yield potentials between the provinces, we used the parameters for one spring wheat and one winter wheat cultivar from the default SWAT database and excluded wheat parameters from the calibration.

Calibration, validation, and uncertainty assessment

The SWAT-CUP was used with the integrated Sequential Uncertainty Fitting Program (SUFI-2) for the sensitivity analysis (Text S III-1, Table S III–1) and the calibration and uncertainty assessments. The SUFI-2 maps all sources of uncertainty (i.e., uncertainty related to parameters, input data, and model structure) that are related to the simulated parameters that are drawn from a sample of 500 Latin hypercube parameter values. The output range of the wheat yields that spans 95% of all simulation results represents the model uncertainty. This range is denoted as the 95% prediction uncertainty band (95PPU). The 95PPU is calculated from the cumulative frequency distribution of all of the simulated yield levels at each point in time. The lower boundary of the 95PPU represents the 2.5th percentile, while the upper boundary represents the 97.5th percentile of the distribution.

The pre-selected parameters that affected the wheat yields in each province were considered for calibration in SUFI-2 (Text S III-2, Table S III-2). To select the parameter values that resulted in the best fits between the observed and simulated yields, we began by specifying large but physically meaningful parameter ranges that ensured that the observed yield data were within the 95PPU. In subsequent iterations, the parameter ranges were narrowed to decrease the parameter uncertainty while ensuring that the observed yields remained within the 95PPU. The narrower parameter ranges were centered on the most recent and best simulation for the subsequent iterations. Iterative calibration was conducted separately for the 28 provinces to account for the large spatial heterogeneity of the geophysical and agricultural conditions in the study area (Faramarzi et al. 2009). A two-year warm-up period was simulated before the validation (1991–1994) and calibration (1995–2006) periods to account for the unknown initial conditions. The warm-up period was used to equilibrate the simulated physical processes to mitigate the unknown initial conditions and exclude them from the analysis.

We used the R and P factors to quantify the goodness-of-fit of the calibration and to assess the uncertainty. The R-factor is the average thickness of the 95PPU band divided by the standard deviation of the observed yield data. The value of the R-factor ranges from zero to infinity, where zero is ideal and values of less than one are desirable. The P-factor is the percentage of the observed yield data that are bracketed by the 95PPU band (maximum value 100%). A 10% measurement error was included for all observed variables when calculating the P and R factors. We used the root mean squared error to assess the fit of the best simulation in the objective function.

Management scenarios and yield gap estimation

We used the calibrated SWAT model to simulate wheat yield potentials and wheat yield gaps using two scenarios. The first scenario (S1) assumed sufficient N fertilizer applications under rainfed conditions. The second scenario (S2) simulated conditions with sufficient N fertilizer under irrigated conditions. In this case, the yields were only influenced by the biophysical conditions and the crop cultivar. The automatic application options for N and water were used to eliminate N stress under S1, and N and water stress under S2.

We ran all simulations for every year in the calibration period (1995–2006) to capture and analyze the impacts of the annual weather conditions on the yield potentials. In both scenarios, the yield gaps for each year were calculated for 1995–2006 from the differences between the observed and simulated yield potentials of the particular year.

Results and discussion

On average, 78% (P-factor = 0.78) of the observed wheat yields for calibration and 82% (P = 0.82) for validation were within the simulated uncertainty bands (Figure III–4, a and b, and Table III-1). The R-factors represented the higher uncertainty in the regions that were dominated by spring wheat (Table S III-3). Fertilizer use was lower in most of the spring wheat regions, thus, the yields were more contingent on soil organic carbon contents and crop rotation practices in these regions (López-Bellido et al. 1996). The lack of reliable soil data and crop rotation practices potentially caused the higher uncertainty that was observed in the simulated yields for the spring wheat regions.

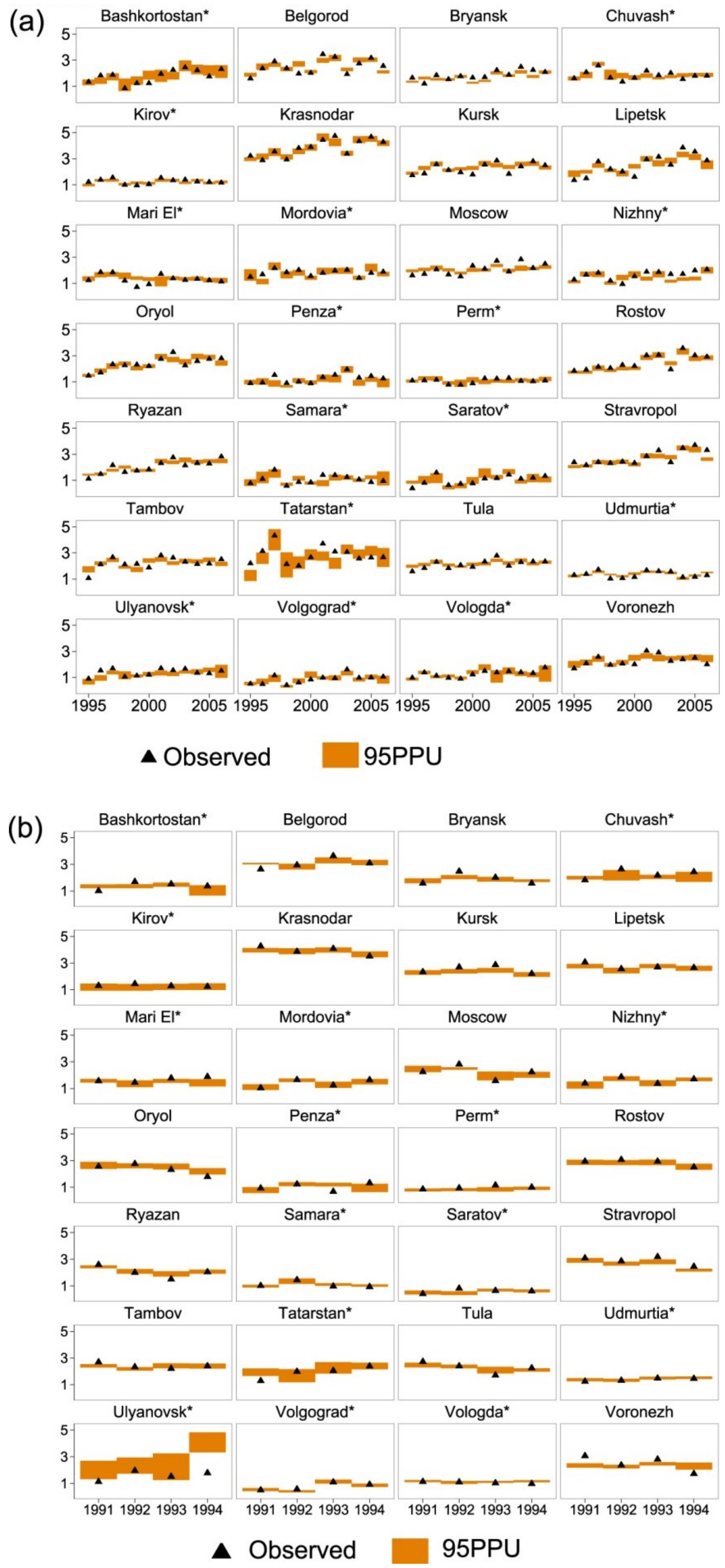


Figure III-4: Comparison of observed yield (t ha^{-1}) with 95PPU of simulated wheat yield (t ha^{-1}) for calibration (A) and validation (B). Asterisk indicates areas dominated by spring wheat.

Table III-1: Calibration and validation statistics (province-level average). *Note* that calibration and validation statistics for all of the provinces are in Table S III-3.

		P-factor	R-factor
Spring wheat	Calibration	0.82	1.34
	Validation	0.82	1.58
Winter wheat	Calibration	0.78	0.64
	Validation	0.90	1.06

We obtained average (i.e., from 1995 to 2006) 95PPUs of the yield potentials for spring wheat of between 2.68 and 3.49 t ha^{-1}under S1 and between 4.63 and 4.82 t ha^{-1} under S2 in European Russia. For winter wheat, the average yield potentials were 4.30–4.63 t ha^{-1} under S1 and 5.45–5.58 t ha^{-1} under S2. The uncertainty was higher under S1 (rainfed) than under S2 (irrigated), particularly for the spring wheat regions (see also Figure S III–1). The average winter wheat yield potentials under S2 were more than 2 t ha^{-1} lower than the average yield potential of winter wheat throughout Russia according to Liu et al (2007), who conducted global simulations using the EPIC model (2007). Conversely, our S2 results were approximately 2 t ha^{-1} greater than the estimate by Licker et al (2010), who approximated yield gaps by comparing observed and maximum yield values in locations with similar soil moisture and temperature characteristics on a global scale in 2000. However, the yield potentials based on biophysical analogs are lower. Thus, the yield gaps are smaller than those estimated from models that simulate potential crop growth under optimal conditions. Even the most advanced wheat and rice systems only approach 70–85% of the yield potential that is simulated by crop growth models. This result occurs because farmers strive to maximize profits rather than yields (Cassman et al. 2003; Lobell et al. 2009; Van Wart et al. 2013b).

The yield potentials for spring and winter wheat increased form the north to south under S1 and S2 due to the higher solar energy supply, longer growing season and better soil conditions in the south (Figure III–5, A and B). The largest and smallest yield potentials were simulated in S2 for Stavropol (6.77–6.84 t ha^{-1}) in the south and for Vologda (4.14–4.23 t ha^{-1}) in the north, respectively.

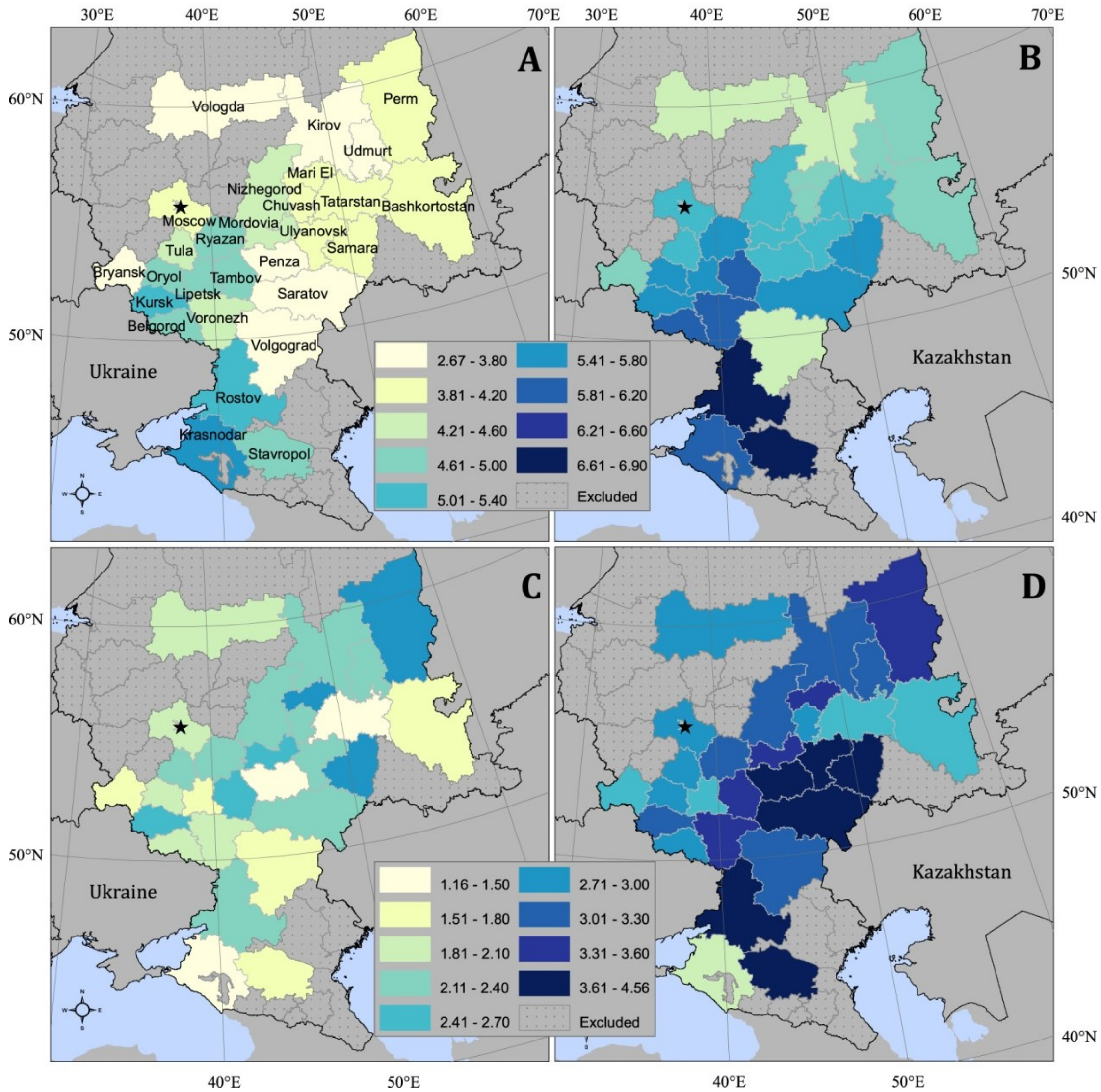


Figure III-5: Yield potentials (t ha^{-1}) under S1 (rainfed conditions, (A)) and S2 (irrigated conditions, (B)); yield gaps (t ha^{-1}) under S1 (C) and S2 (D). All maps show averages from 1995 to 2006.

The average 95PPU of the yield gaps for the winter and spring wheat were 1.51–2.10 t ha^{-1} (44–52% of the potential yield) for S1 and 3.14–3.30 t ha^{-1} (62–63%) for S2. Thus, relaxing nutrient stress is important for increasing wheat yields in European Russia. For winter wheat, the average yield gaps were 1.95–2.27 t ha^{-1} (45–49%) for S1. The absolute yield gaps were lower for spring wheat, with 1.22–2.03 t ha^{-1} for S1. However, the relative yield gaps were generally higher for spring wheat (45–58%) than for winter wheat (45–49%). The yield gaps for spring wheat (3.18–3.36 t ha^{-1}, 68–70%) were substantially greater than those for winter wheat in S2 (3.03–3.16 t ha^{-1}, 55–57%).

The average yield gap for S2 was 65–160% greater than that of S1 for spring wheat, but only 39–55% greater for winter wheat. This difference reflected the continental climate in the spring wheat regions with lower precipitation and more frequent and intense droughts. Precipitation and the number of days per year when water stress limits plant growth affect the spring wheat yields, especially in southeastern European Russia such as in Volgograd (Figure III–6; the correlation between precipitation and simulated water stress days with $R^2 = -0.48$, and between the observed wheat yields and simulated water stress days with $R^2 = 0.7$). Water stress crucially limits potential yields under S1, particularly in the spring wheat regions. Therefore, irrigation could substantially increase the average yield potential (Figure III–5, B), as demonstrated by the field experiments that were conducted in Volgograd (Grigorov et al. 2007).

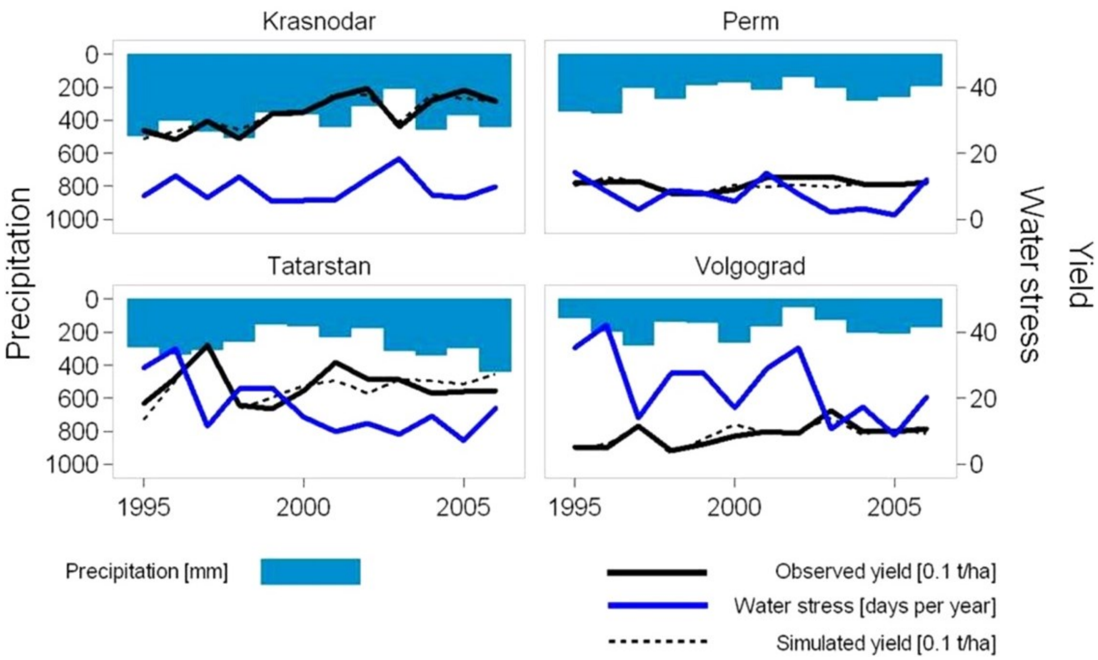


Figure III-6: Annual precipitation (mm) for the growing period; wheat yields (0.1 t ha^{-1}) and the number of days per year when water stress limits plant growth. Simulated yields and days with water stress were obtained from the best SWAT simulation.

At the provincial level, the average yield gaps were greater than 1.5 t ha^{-1} in most provinces for both S1 and S2 (Figure III–5, C and D). For S1, the yield gaps were generally larger in northern European Russia, where the crop growth was mainly constrained by nutrient availability. Shortages in nutrient supplies and water and high daily temperature peaks limit the wheat yields in southern European Russia. We observed that the smallest yield gaps occurred in Krasnodar and Tatarstan for S1, which have fertile soils, above-average and stable precipitation (Figure III–6), and had above-average N applications between 1995 and 2006 (70 kg ha−1 in Tatarstan and 51 kg ha^{-1} in Krasnodar compared with 20 kg ha^{-1} for European Russia as a whole, ROSSTAT 2014).

Considerable annual fluctuations in yield potentials and yield gaps occurred for S1 (Figure III–7) due to the high interannual climatic volatility, particularly in the spring wheat regions in the southeastern region of European Russia (Penza, Samara, Saratov, Ulyanovsk, and Volgograd; Figure III–6). The high interannual volatility in the yield potential was much lower under irrigated conditions (S2, Figure III–7). The high volatility of potential yields under rainfed conditions underscores the importance of investigating the year-to-year variations in the regions where climate fluctuations are important for harvest outcomes. The static representations of crop yield potentials in these environments obscure the climate-driven volatility of the crop yields.

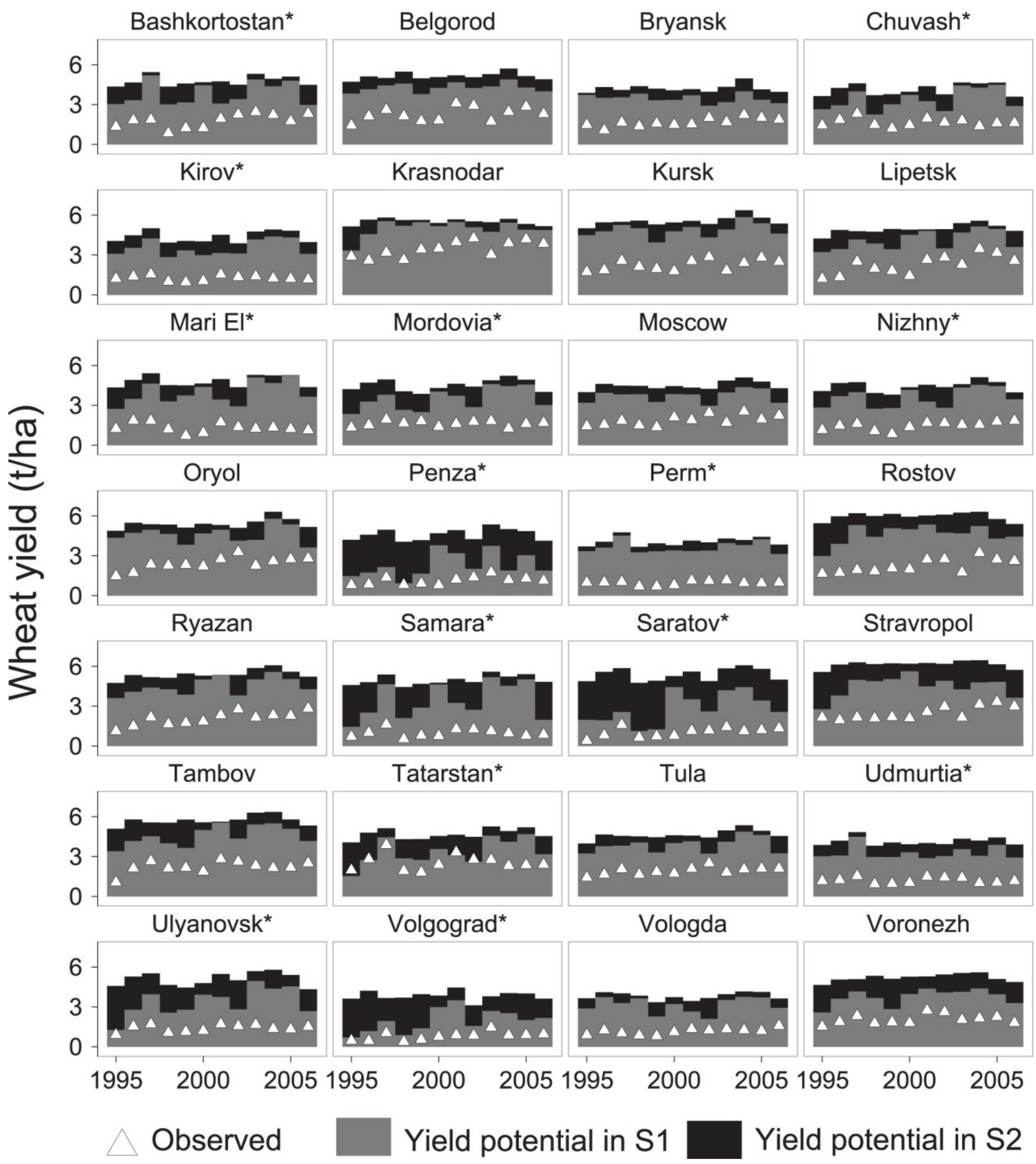


Figure III-7: Observed yield and yield potentials (t ha^{-1}) under S1 (rainfed conditions) and S2 (irrigated conditions). Asterisk indicates areas dominated by spring wheat.

The yield potentials were more stable for S1 between 1995 and 2006 in northern European Russia (for example, Kirov, Perm, Udmurtia, Vologda; Figure III–7) because the precipitation patterns were less volatile and the yield reductions due to water stress were weaker. For example, the correlation between precipitation and water stress days was small in Perm (Pearson $R^2 = 0.19$) and non-existent between the yields and the number of water stressed days (Pearson $R^2 = 0.01$) (Figure III–6). However, the sowing area in the northern region of European Russia and its importance for agricultural production are relatively small. Expected climate change will most likely prolong the growing season in northern latitudes (Kiselev et al.

2013; Olesen and Bindi 2002), which will result in higher future yield potentials (Dronin and Kirilenko 2011) and provide incentives for reusing abandoned agricultural lands (Schierhorn et al. 2012). Increasing yield potentials and decreasing crop shortfalls due to drought suggest that northern European Russia may become a more important grain-producing region.

We detected the highest average yield gaps of up to 4 t ha^{-1} for S2 in southeastern European Russia along the border of Kazakhstan (Volgograd, Saratov, Penza, Samara, and Ulyanovsk; Figure III–5, D). The yield potentials and yield gaps in this region were substantially lower under S1 (rainfed) than under S2 (irrigated) in most years (Figure III–7). In this case, increasing N application will not increase the yield potentials due to the crop-water limitations, which are similar to the co-interactions between yields, fertilizer, and water availability in the Australian breadbasket (Bryan et al. 2014) and rainfed Mediterranean regions (López-Bellido et al. 1996). Moreover, the high annual volatility of precipitation (Figure III–6) and the ensuing frequent crop failures contribute to the observed low applications of intermediate inputs (fertilizer, in particular) because the agriculture profits become highly uncertain in the absence of adequate agricultural insurance schemes (Dronin and Kirilenko 2011; Kiselev et al. 2013). One promising avenue for increasing and stabilizing yields in the regions with high climatic volatility is the development and cultivation of drought-resistant wheat varieties (Challinor et al. 2014; Grabovets and Fomenko 2008; Howden et al. 2007). Improved crop rotations and no-till practices are relevant adaption strategies for climate change (Aguilera et al. 2013; Smith and Olesen 2010).

Unfortunately, no data are available at the pan-Russian scale that allows us to include crop varieties and crop rotations in the simulations. Therefore, we disregarded alternative crop rotations and we relied on the simplified representation of wheat varieties with the default wheat parameters of the SWAT model, akin to other large-scale crop simulations (Bondeau et al. 2007; Liu et al. 2007; Nelson et al. 2010). This prohibited us from analyzing the effect of different wheat varieties and rotations on wheat yields, but it permits between-site comparison of yield potentials subject to the climate signal and to regional management.

Conclusions

Crop yields were low and the yield gaps were high across most of the fertile agricultural lands of European Russia. Unfortunately, little conclusive evidence has been obtained regarding the potentially attainable yields and the drivers of the yield gaps in European Russia. To address this gap, we simulated the annual wheat yield potentials for European Russia between 1995 and 2006 using a crop growth model that was calibrated with provincial-level agricultural inventory data. On average, yield gaps were 1.51–2.10 t ha^{-1} and 3.14–3.30 t ha^{-1} for rainfed and irrigated conditions, respectively. The yield gaps varied considerably across space and time, driven by the high interannual volatility of the precipitation patterns and the input intensity.

Despite the large yield gaps, we caution against exaggerated yield expectations. First, yield potentials decrease substantially during drought years, particularly in the breadbaskets of southern Russia where the climatic conditions are volatile and the current cropping systems are mainly rainfed. The yield gaps under irrigated conditions are highly speculative and depend on the available water resources and on the economic feasibility of expanding the irrigation capacity. The high likelihood of drought has important implications for farm entrepreneurs who aim to maximize their profits rather than yields because investments in intermediate inputs, such as fertilizer, are lost during drought years when the yields collapse.

Policies that improve agricultural insurance schemes may successfully reduce the investment risks in the Russian breadbaskets, which would increase input intensity and production. In addition, strategies that incentivize the use of existing water resources and improve the efficiency of water use may enhance production. Such initiatives will become increasingly important as the frequency of summer drought and heat stress increase with future climate change (Alcamo et al. 2007; Kiselev et al. 2013), which would lead to higher crop yield volatility. Our results are helpful for quantifying potential crop production and for pinpointing management strategies and research initiatives that will help improve yields and close yield gaps in this globally important agricultural region.

Acknowledgments

This manuscript has benefited from the contributions of A Balmann, J K Thakur, S Neumann, M Volk, F Witting, and M Strauch. We are grateful for the financial support of the Leibniz Association's 'Pakt für Forschung', the German Federal Ministry of Education and Research (BMBF) (Code01 LL0901A), the German Federal Ministry of Food and Agriculture (BMEL) (GERUKA), and the European Union (FP7-ENV-2010-265104).

Supporting information

Text S III-1: Sensitivity analysis

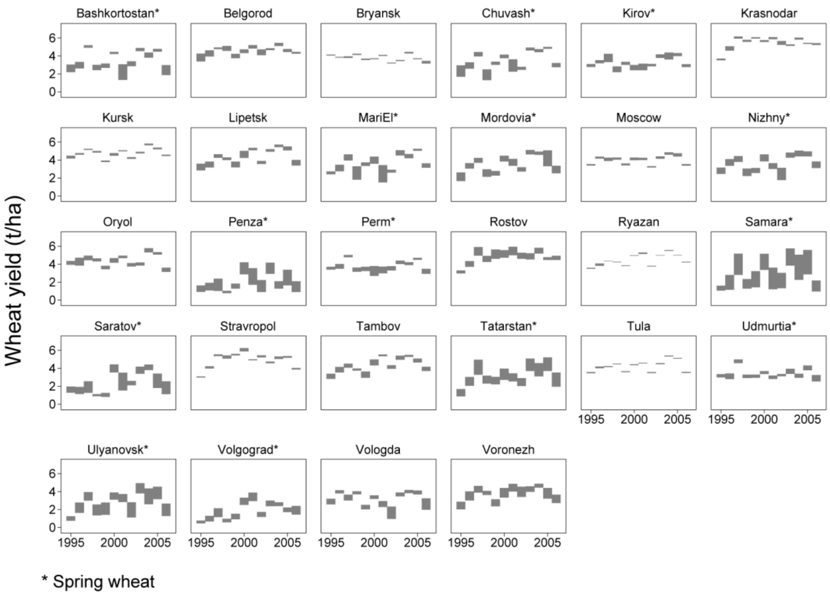
Sensitivity analyses for each of the 28 provinces were conducted to assess the responses of the model to the changes in the input parameters. We pre-selected 28 parameters that are potentially sensitive to wheat yield and pre-defined reasonable parameter ranges based on a literature review, local knowledge, and a one-at-a-time sensitivity analysis using the SWAT Calibration and Uncertainty Program (SWAT-CUP, Abbaspour et al. 2007). The parameters that affected wheat yields in each province were subsequently considered for calibration in the Sequential Uncertainty Fitting Program (SUFI-2).

Text S III-2: Sensitivity results

Parameter sensitivity was reasonably consistent across the provinces (Table S III–1. As expected, the parameters regulating soil fertility (annual N fertilizer supply (FRT_KG), and organic carbon content (CBN)) were among the most sensitive parameters in almost of the provinces. The wheat yield was sensitive to soil-related parameters, such as bulk density (SOL_BD), the fraction of porosity from which anions are excluded (ANION_EXCL), and the saturated hydraulic conductivity. Ina addition, wheat the wheat yields were sensitive to the parameters that regulated the surface and sub-surface water flows, such as the SCS runoff curve number for moisture condition II (CN2), the plant uptake compensation factor (EPCO), the soil evaporation factor (ESCO), and the threshold depth of the water in the shallow aquifer for return flow (GWQMN).

The simulation results were insensitive to most of the groundwater-related parameters. This finding suggests that the soil and plant water availability are not decisively regulated by the parameters that are related to groundwater. The yields were highly sensitive to the available water capacity (AWC) and many of the crop-related parameters. However, we were unable to set realistic ranges for the AWC and crop-related parameters in the sensitivity analysis and calibration because the available data were not precise enough. Instead, comparable and more realistic yield potential estimates were generated by excluding the AWC and crop-related parameters from the calibration. Hence, we set the AWC values at 0.15 and 0.1 for the first and second soil layers, respectively, in all of the simulations and used the default parameters in the SWAT crop database.

A, Without nutrient stress (S1):



B, Without nutrient stress and fully irrigated (S2):

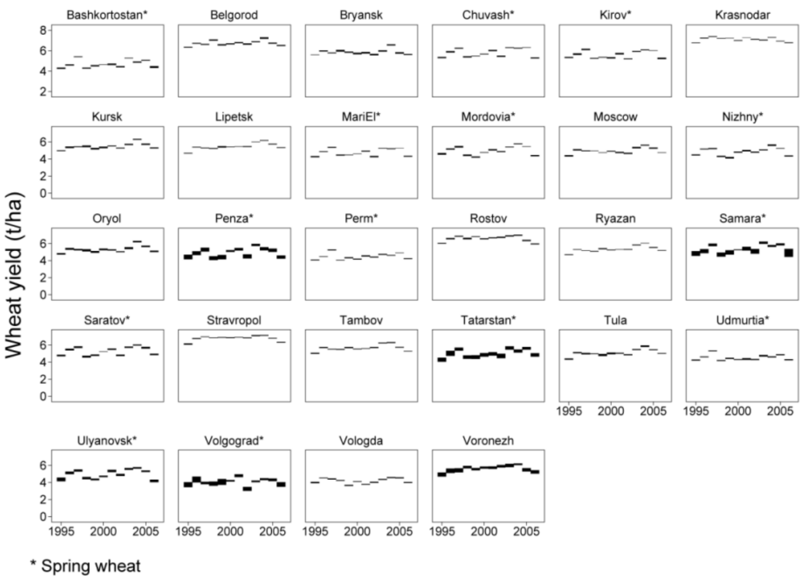


Figure S III-1: Annual yield potential without nutrient stress (S1) (A) and without nutrient and water stress (S2) (B).

Table S III-1: Parameter sensitivity.

Please find the long Table S III-1 here: *http://iopscience.iop.org/1748-9326/9/8/084017/media/erl499977suppdata.pdf*

Table S III-2: Initial parameter ranges for sensitivity analysis and calibration.

Definition	Parameter	Initial range*
Soil evaporation factor	v__ESCO.hru	0.01-1
Plant uptake compensation factor	v__EPCO.hru	0.01-1
Manning's n value for overland flow	v__OV_N.hru	0.01-0.8
Lateral flow travel time (days)	v__LAT_TTIME.hru	0-180
Sediment concentration in lateral and groundwater flow (mg/L)	v__LAT_SED.hru	0-5000
Maximum canopy storage (mm H_2O)	v__CANMX.hru	0-1
Soil bulk density in layer 1 of soil profile (g/cm^3)	v__SOL_BD(1).sol	1.1-1.7
Soil bulk density in layer 2 of soil profile (g/cm^3)	v__SOL_BD(2).sol	1.1-1.7
Organic carbon content in layer 1 of soil profile (% soil weight)	v__SOL_CBN(1).sol	1-3
Organic carbon content in layer 2 of soil profile (% soil weight)	v__SOL_CBN(2).sol	0-2
Moist soil albedo in layer 1 of soil profile	v__SOL_ALB(1).sol	0-0.25
Moist soil albedo in layer 2 of soil profile	v__SOL_ALB(2).sol	0-0.25
Fraction of porosity from which anions are excluded	v__ANION_EXCL.sol	0.2-0.8
Saturated hydraulic conductivity in layer 1 of soil profile (mm/hr)	v__SOL_K(1).sol	0-2000
Conductivity in layer 2 of soil profile(mm/hr)	v__SOL_K(2).sol	0-2000
Potential or maximum crack volume of the soil profile	v__SOL_CRK.sol	0-1

Definition	Parameter	Initial range*
USLE equation soil erodibility (K) factor in layer 1 of soil profile	v__USLE_K(1).sol	0-0.65
USLE equation soil erodibility (K) factor in layer 2 of soil profile	v__USLE_K(2).sol	0-0.65
Electrical conductivity in layer 1 of soil profile (dS/m)	v__SOL_EC(1).sol	0-100
Electrical conductivity in layer 2 of soil profile (dS/m)	v__SOL_EC(2).sol	0-100
Initial depth of water in the shallow aquifer (mm H_2O)	v__SHALLST.gw	0-1000
Initial depth of water in the deep aquifer (mm H_2O)	v__DEEPST.gw	0-1290
Groundwater delay time (days)	v__GW_DELAY.gw	0-500
Base flow alpha factor (days)	v__ALPHA_BF.gw	0-1
Threshold depth of water in shallow aquifer required for return flow to occur (mm)	v__GWQMN.gw	0-5000
Groundwater revap. coefficient	v__GW_REVAP.gw	0.02-02
Deep aquifer percolation fraction	v__RCHRG_DP.gw	0-1.1
Initial groundwater height (m)	v__GWHT.gw	0-25
Specific yield of the shallow aquifer (m^3/m^3)	v__GW_SPYLD.gw	0-0.4
Initial concentration of nitrate in shallow aquifer (mg N/L or ppm)	v__SHALLST_N.gw	0-10
Concentration of soluble phosphorus in groundwater (mg N/L or ppm)	v__GWSOLP.gw	0-1000
Half-life of nitrate in the shallow aquifer (days)	v__HLIFE_NGW.gw	0-365
Amount of fertilizer applied (kg/ha)	r__FRT_KG.mgt	0.3-0.3

* Minimum and maximum values of the parameter range over 28 provinces.

Table S III-3: Calibration and validation statistics for all of the provinces.

1. Spring wheat

Province	Period*	P-factor	R-factor	RMSE
Vologda	C	1	1.74	0.0061
	V	0.75	0.59	
Udmurtia	C	0.75	0.94	0.0232
	V	1	1.9	
Kirov	C	0.75	0.94	0.0171
	V	1	1.9	
Perm	C	1	1.81	0.0233
	V	0.75	0.93	
Chuvash	C	0.92	1.02	0.0488
	V	1	1.66	
Mari El	C	0.67	1.07	0.0569
	V	0.75	1.54	
Bashkortostan	C	0.92	1.42	0.0532
	V	0.5	1.56	
Nizhny	C	0.58	1.01	0.0922
	V	1	1.49	
Tatarstan	C	0.75	1.55	0.1599
	V	0.75	1.76	
Mordovia	C	0.92	2.07	0.0337
	V	1	1.37	
Ulyanovsk	C	0.75	1.51	0.0661
	V	0.5	4.79	
Samara	C	0.75	1.4	0.0401
	V	1	0.91	
Penza	C	0.75	1.3	0.0407
	V	0.75	1.53	
Saratov	C	0.92	1.26	0.0557
	V	0.75	0.91	
Volgograd	C	0.92	1.09	0.0191
	V	0.75	0.87	
Average	C	0.82	1.34	
	V	0.82	1.58	

* C: calibration period (1995–2006); V: validation period (1992–1995); RMSE: root mean squared error

2. Winter wheat

Province	Period*	P-factor	R-factor	RMSE
Moscow	C	0.58	0.58	0.0078
	V	1	0.96	
Tula	C	0.92	0.73	0.0369
	V	1	0.87	
Ryazan	C	0.67	0.49	0.0529
	V	0.75	0.78	
Bryansk	C	0.42	0.52	0.0682
	V	0.75	0.76	
Oryol	C	0.92	0.71	0.0512
	V	1	1.2	
Lipetsk	C	0.75	0.51	0.1313
	V	1	1.35	
Tambov	C	0.67	0.7	0.0941
	V	1	1.18	
Kursk	C	0.75	0.72	0.0687
	V	1	1.22	
Belgorod	C	0.75	0.57	0.0883
	V	0.75	0.88	
Voronezh	C	0.92	1.02	0.0568
	V	0.5	0.64	
Rostov	C	0.92	0.55	0.0332
	V	1	1.55	
Krasnodar	C	1	0.7	0.0479
	V	1	1.35	
Stravropol	C	0.83	0.58	0.0817
	V	1	1.01	
Average	C	0.78	0.64	
	V	0.9	1.06	

* C: calibration period (1995–2006); V: validation period (1992–1995); RMSE: root mean squared error.

Chapter IV The potential of Russia to increase its wheat production through cropland expansion and intensification

Global Food Security, Vol. 3 (2014), No. 3-4, S.133-141.

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Abstract

Russia is a major player in the global wheat market, but extensive unused land resources and large yield gaps suggest that wheat production can be substantially increased. We combined time series of cultivated cropland, abandoned cropland and yield gap estimates to assess the potential production of wheat in European Russia. Current wheat production is constrained by volatile inter-annual precipitation patterns and low applications of nitrogen fertilizers. We demonstrate that modest increases in the crop productivity and the re-cultivation of the recently abandoned croplands could increase wheat production by 9 to 32 million tons under rainfed conditions. Increases in the wheat yields, particularly within the fertile black soil belt in southern European Russia, will contribute the major share of the prospective production increases. Frequently recurring droughts, likely exacerbated by future climate change, and adverse market conditions jeopardize the exploitation of the production potentials. Improved adaptation to the volatile climate conditions and substantial institutional and political reforms in the agricultural sector are necessary to leverage the agricultural production potential of Russia.

Introduction

The worldwide demand for agricultural products will grow considerably in the coming decades because of increasing populations, changing diets and the increasing use of bioenergy (Regmi and Meade 2013; Tilman et al. 2011). This increasing demand can be satisfied by expanding cultivated areas, but the ecological and social trade-offs of further land expansion are high in most regions (Lambin et al. 2013). Most future increases in agricultural production are therefore likely to be generated by increasing the output per unit of land, that is, from higher land productivity.

The scope for future increases in land productivity is substantial in many developing and transition countries where the differences between the potential yield under optimum management and the yields that are actually achieved by farmers, i.e., yield gaps, are large (Affholder et al. 2013; Hall et al. 2013; Lu and Fan 2013; van Ittersum and Cassman 2013). Reductions in the yield gaps will typically require higher and more efficient input use (fertilizers, pesticides, and water) and improvements in crop management (Evans and Fischer 1999). Moreover, to decrease yield gaps necessitate investments in infrastructure, education and agronomic research, as well as supportive agricultural policies (George 2014; Neumann et al. 2010; Tilman et al. 2011).

One country that is of particular interest for increasing the supply of agricultural products is the Russian Federation. Russia has emerged as a leading player in the world grain market; the country was among the top five wheat-exporting countries between 2006 and 2011 (FAO 2014). Russia can increase its grain production substantially and thus expand its position in the world grain markets because of low yields and large areas of idle former agricultural land (Lioubimtseva and Henebry 2012). However, it remains elusive how large the untapped grain potentials of Russia are and which environmental trade-offs are associated with land re-cultivation and intensification.

The dissolution of the Soviet Union in 1991 and the subsequent institutional reforms triggered widespread agricultural land abandonment in Russia (Prishchepov et al. 2013). As a result, vast areas of former cropland can potentially be re-cultivated. However, a substantial carbon sink developed in the soils and in the successional vegetation on the cropland that was abandoned soon after the dissolution, and the re-cultivation of these lands would lead to large carbon emissions (Poeplau et al. 2011; Schierhorn et al. 2013).

The crop yields in Russia decreased after the dissolution of the Soviet Union, rebounded toward the late 1990s (ROSSTAT 2014), but remained much lower than the yields that are achieved in comparable natural conditions outside the country (FAO 2014; Licker et al. 2010). The main reason for the large yield gaps in wheat cultivation are severe limitations of water and nutrient application (Nosov and Ivanova 2011; Schierhorn et al. 2014), mainly caused by financial and managerial shortcomings at the farm level, as well as institutional shortcomings and adverse infrastructure (Bokusheva et al. 2011).

Here, we estimate the potential of European Russia for wheat production. European Russia produces 75% of Russia's wheat output and provides the bulk of Russian wheat exports (ROSSTAT 2014). To quantify potential production increases, our specific objectives are first to estimate the production potential of existing cropland by combining cropland data with estimates of yield gaps in wheat cultivation. Second, we quantify the production potential from re-cultivating abandoned cropland under consideration of the carbon emissions that are released from the successional vegetation and soils. Finally, we discuss the production potential in light of volatile climate conditions and the structural and socio-political constraints that may jeopardize future increases in the wheat production in Russia.

Land endowment

Official agricultural inventory statistics report a total sowing area of 77 million hectares (Mha) for Russia in 2011, down from 118 Mha in 1990 (ROSSTAT 2014, Figure IV-1). This implies a decrease in the sowing areas by 35% or 41 Mha, equivalent to the entire sowing areas in 2010 of France, Germany and Spain combined (Eurostat 2013). Official inventory statistics of the sowing area are reliable data of land abandonment for Russia (Ioffe et al. 2004; Nefedova 2011), and match well with the remote sensing estimates of abandoned agricultural lands (Alcantara et al. 2013) and of sowing areas (de Beurs and Ioffe 2013).

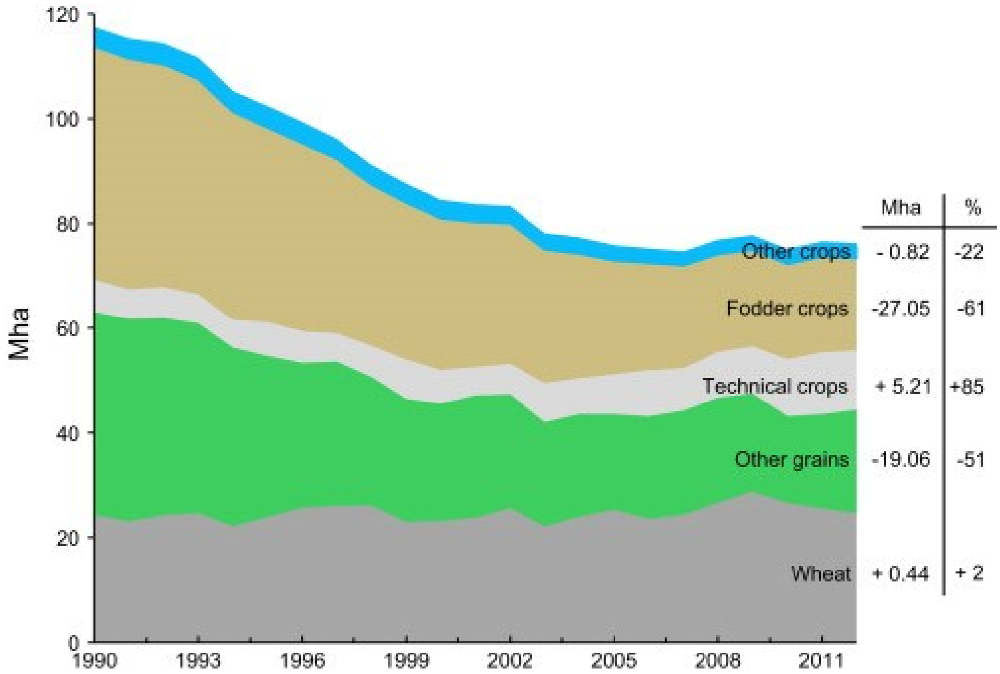

Figure IV-1: Sowing areas (million hectares, Mha) in Russia. Per cent and absolute change between 1990 and 2012 on the right. Other crops: potatoes and vegetables; fodder crops: annual and perennial grasses and root vegetables; technical cultures: sunflower, sugar beet, soybean, and rapeseed; other grains: barley, rye, and oat. The data are from ROSSTAT (2014).

The contraction of cropland in Russia has been triggered by the liberalization of previously subsidized input and output prices, poorly functioning land markets, and increasing international competition (Lerman and Shagaida 2007; Liefert and Liefert 2012; Prishchepov et al. 2013). In particular, the profitability of livestock production decreased after the dissolution of the Soviet Union (Lioubimtseva and Henebry 2012), mainly driven by the abrupt elimination of state subsidies to the livestock sector. In response, the number of cattle decreased by 65%, from 57 million in 1990 to 20 million in 2012 (ROSSTAT 2014). The contraction of the livestock production was coextensive with the sharp decrease in fodder crops (27 Mha or 61%, Figure IV-1). Grains other than wheat (for example, barley and rye), which are partly used as fodder for livestock, also decreased substantially between 1990 and 2012 (19 Mha or 51%, Figure IV-1). The area that was cultivated with wheat remained fairly stable during this period mainly because wheat has been the main staple crop in Russian food consumption and due to the emerging export opportunities of wheat.

European Russia contained 72% or 55.7 Mha of the total sowing area of Russia (77 Mha) in 2011 (ROSSTAT 2014). The sowing areas cluster along the fertile black soil belt that stretches from southern to eastern European Russia (the hatched area in Figure IV-2). Fewer sowing areas are found outside the black soil belt in temperate European Russia (north of latitude 55°; Figure IV-2), where the cropland suitability is considerably lower (Schierhorn et al. 2013). The sowing area in European Russia decreased by 33% or 27.2 Mha after the dissolution of the Soviet Union (ROSSTAT 2014). The highest rates of decrease in the sowing areas occurred in the region north of the black soil areas. In contrast, the smallest decreases occurred within the black soil belt in southern European Russia, which is also the primary breadbasket of Russia. Most of the post-Soviet abandonment of cropland occurred soon after the dissolution of the Soviet Union (Schierhorn et al. 2013).

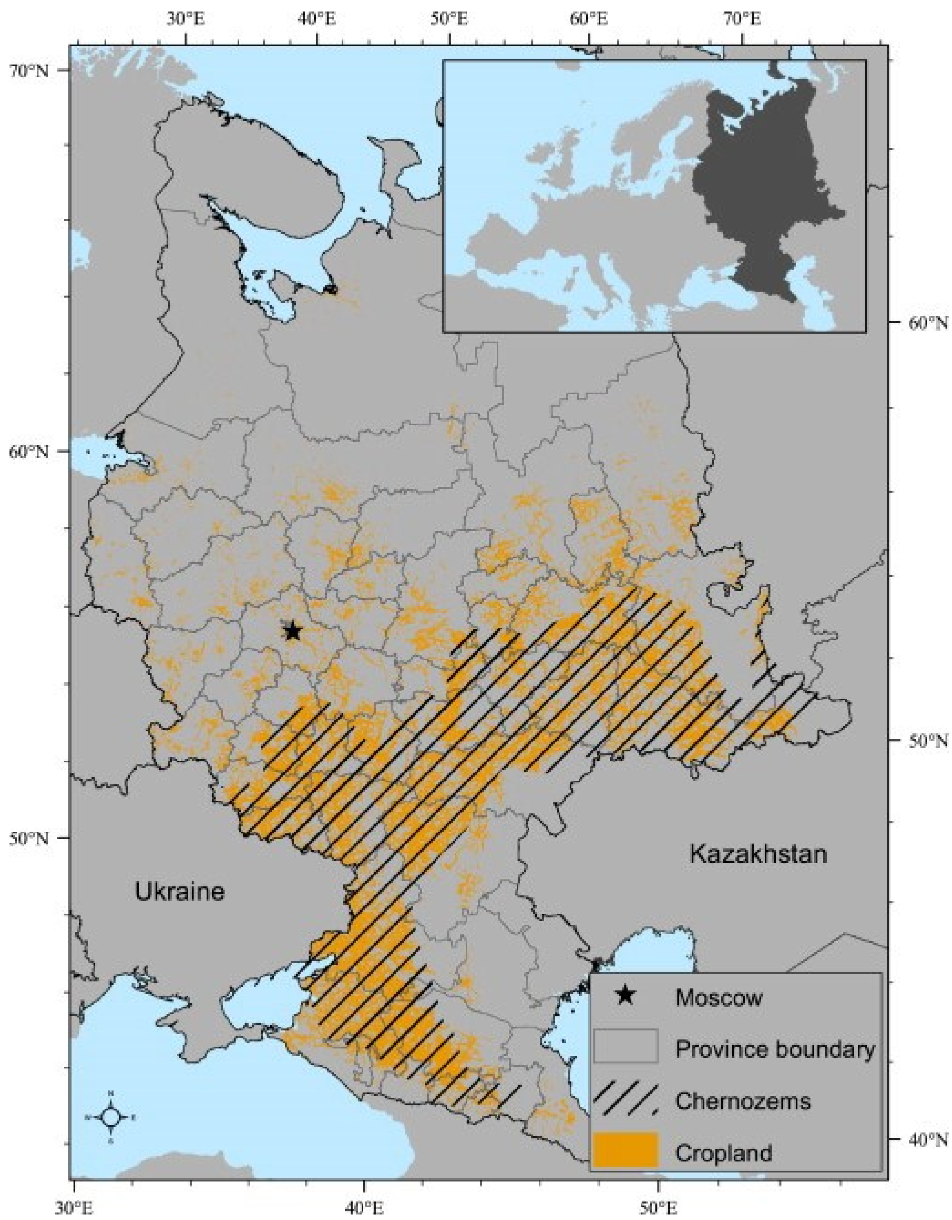

Figure IV-2: Distribution of croplands in 2011 and the location of the black soil belt in European Russia. The cropland data are from Schierhorn et al. (2013).

Wheat yields and wheat yield gaps

The fading state's support for agriculture and the liberalization of markets along with weak institutional conditions after the dissolution of the Soviet Union contributed to the strong reduction of the agricultural input use (mainly fertilizers) in Russia, particularly during the early 1990s (Rozelle and Swinnen 2004). In combination with poor weather conditions during the 1990s (Liefert and Liefert 2012; Schierhorn et al. 2014), the average wheat yields decreased from 1.93 t ha^{-1} between 1990 and 1992 to 1.49 t ha−1 between 1994 and 1996, a decrease of 23% (Figure IV-3). Figure IV-3 also reveals the high inter-annual yield variability that was mainly caused by the volatile weather conditions, especially in southern European Russia.

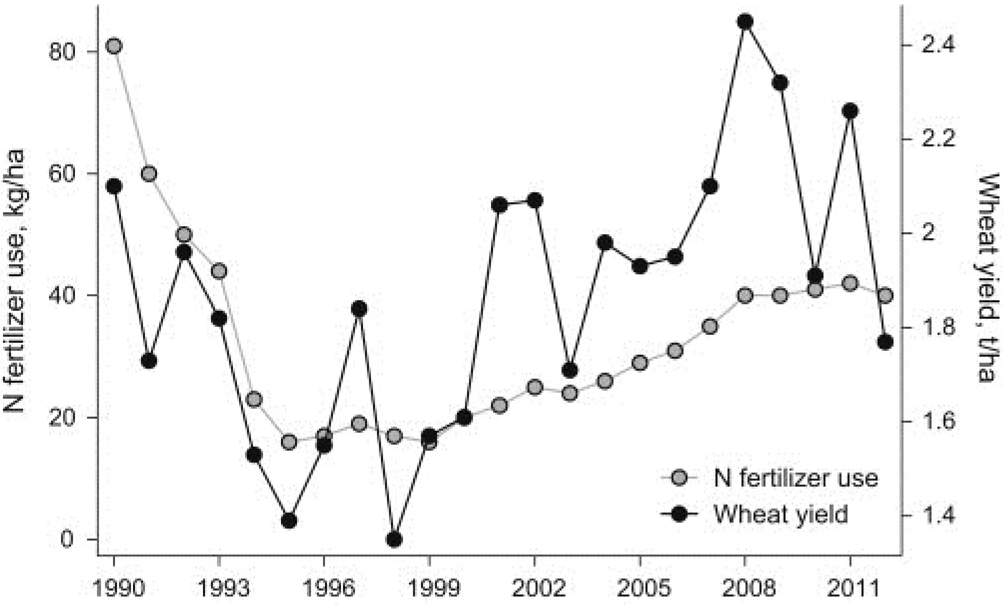

Figure IV-3: N fertilizer use (kg/ha) and wheat yields (t ha−1) in Russia. The data are from ROSSTAT (2014).

In the late 1990s, the wheat yields in Russia began to increase again (Figure IV-3), partially as a result of the increase in the agricultural input intensity and higher production efficiency, mainly triggered by the emergence of large, profit-oriented corporate farms with abundant capital (Liefert et al. 2010; Salputra et al. 2013). For example, nitrogen (N) fertilizer application in cereal production surged by 150% between 1999 and 2012, from 16 to 40 kg/ha (Figure IV-3). Moreover, better weather conditions after 1998 contributed to the increase in wheat yields in Russia (Liefert and Liefert 2012; Schierhorn et al. 2014). The wheat yields rebounded approximately to the 1990 level by 2007, although N fertilizer application was applied at only half of the rate during late Soviet times (Figure IV-3). The low application rates were compensated for by higher-quality wheat cultivars (Liefert et al. 2010). Nevertheless, the contemporary wheat yields in Russia are three to four times lower than the average yields in Germany and France (FAO 2014). However, there are also considerable regional differences in the wheat yields across European Russia. For example, in 2008, a year with good weather conditions, the average wheat yields were 3.8 t ha^{-1} within the fertile black soil belt in southern European Russia, but only 1.97 t ha^{-1} in other areas (ROSSTAT 2014).

Material and methods

We quantified the wheat production that can potentially be achieved in European Russia first by assuming different degrees of yield gap closure on existing cropland and second by re-cultivating abandoned croplands with the same assumptions of yield gap closure.

Estimation of the production potential on existing cropland

We quantified the potential wheat production on existing cropland by gradually increasing the wheat yields towards the potential yield. To obtain the biophysical yield potentials, we simulated plant growth for winter and spring wheat at the provincial (*oblast*) level across European Russia (Schierhorn et al. 2014). We used the Soil and Water Assessment Tool (SWAT), which is a process-based, spatially distributed landscape model that relies on a simplified version of the erosion productivity impact calculator (EPIC, Williams et al. 1989) for plant growth simulation (Arnold et al. 1998). Our SWAT application simulates plant growth based on the reported N application from official statistics and under water-limited as well as irrigated conditions. Otherwise, we enforced optimal growing conditions in the model, that is, without stress for the crops due to weeds, pests, and diseases (Neitsch et al. 2005).

In SWAT, the study area is divided into sub-basins based on topography. We selected the 28 sub-basins (one per province) with the largest area of cropland and with more than 25,000 ha under wheat cultivation in 2006. The main input data are the digital elevation model GTOPO30 from the U.S. Geological Survey (USGS), monthly climate data from the Climate Research Unit (CRU, TS 1.0 and 2.0, *http://www.cru.uea.ac.uk/cru/data/hrg.htm*) were used to generate daily precipitation, temperature, solar radiation and wet-day frequency with the SWAT weather generator (Arnold and Fohrer 2005), and soil parameters from the Harmonized World Soil Database (FAO et al. 2012). We used the annual wheat yields, N fertilizer use, and sowing area of wheat from official provincial-level statistics (ROSSTAT 2014) to calibrate the SWAT model and we validated the model with data from 1991 to 1994 (Schierhorn et al. 2014). The data on the growing season length of wheat were obtained from the United States Department of Agriculture (USDA 2013), Rukhovich et al. (2007), and GOSSORT (2014).

The calibrated model was used to simulate wheat yield potentials with an optimal N supply for both water-limited (rainfed) conditions and irrigated conditions (see Schierhorn et al. (2014), for a detailed description of the model calibration and uncertainty assessment). Other measures to increase the yields (for example, the selection of different wheat cultivars) were not assessed. We simulated the yield potentials separately for all 28 sub-basins in European Russia to better account for the large spatial heterogeneity in environmental conditions. Our simulation period from 1995 to 2006 includes years with sufficient precipitation (mainly after 2000) as well as severe drought years (mainly before 2000).

We used the average reported wheat yields of all of the provinces between 1995 and 2006 to calculate the baseline production. The baseline for cultivated area consists of the average sowing area for grains in all of the provinces between 1995 and 2006 (34 Mha) under the assumption that wheat can potentially be cultivated in the entire grain area. We then multiplied for each province the average wheat yield with the average grain area to generate a baseline output of wheat production (59 million tons, Mt), against which we compared the additional wheat output that can be attained by yield growth on existing croplands. The uncertainty of the wheat yield simulation is visualized with the 95% prediction uncertainty (95PPU) band that represents the model uncertainty excluding the lower and upper 2.5th percentiles of the simulated values (Abbaspour et al. 2007). For the sake of brevity, we reported all of the results using the mean 95PPU of wheat production potential.

Estimation of production potential on abandoned cropland

The expansion of crop production on abandoned cropland is often assumed to be a relatively sustainable way to increase the supply of agricultural products (Cai et al. 2010; Campbell et al. 2008). However, abandoned croplands store considerable amounts of carbon in successional vegetation and soils, depending on the natural conditions and the duration of succession (Kurganova et al. 2014; Post and Kwon 2000). Carbon sequestration on abandoned croplands in European Russia increased significantly after approximately ten years of abandonment (Schierhorn et al. 2013). Consequently, carbon emissions from re-cultivating abandoned cropland increase with time since abandonment. Moreover, the re-cultivation of older successional vegetation is costly because the mature vegetation including soil-penetrating roots must be removed (Larsson and Nilsson 2005; USDA-FAS 2008).

We used annual time series of post-Soviet cropland abandonment (Schierhorn et al. 2013) that accounted for the increasing carbon emission and re-cultivation costs that are associated with re-cultivation. We assumed that re-cultivation commences on the recently abandoned cropland and progressively integrates older abandoned fields. Approximately 9.5 Mha (35%) of the total 27.2 Mha of abandoned cropland in European Russia was abandoned after 2000, and we assume that re-cultivation takes place on these 9.5 Mha because of lower carbon emissions. However, most of these abandoned croplands are located in temperate European Russia, where the share of grain cultivation is low. We assumed that the share of wheat matched the share of grain in the total sowing area in each province, which leaves only 4.4 Mha available for re-cultivation with wheat. We multiply these 4.4 Mha with the potential yield to generate wheat production potentials on abandoned cropland.

Results

We found average relative yield gaps (the ratio of potential minus actual yield to potential yield) of 62-63% (3.14-3.30 t ha^{-1}) between 1995 and 2006 for irrigated conditions and substantial but smaller yield gaps for rainfed conditions (44-52% or 1.51-2.10 t ha^{-1}). The yield gap analysis revealed that water availability and fertilizer application are critical for increasing wheat yields. However, frequently recurring droughts in the black soil area induced large annual fluctuations in the yield potential.

Production potential of existing cropland

Under rainfed conditions without N stress, the reduction of the time-averaged wheat yield gap in each province to 60% and 80% of the province's yield potential would increase the baseline wheat output of 59 Mt (see 4.1, Figure IV-4) by 3 and 23 Mt, respectively. Closing the average yield gap to 60% and 80% of the yield potential under irrigated conditions would generate an additional 30 and 60 Mt of wheat, respectively (Figure IV-4). A complete yield gap closure would result in an additional wheat production of 44 Mt under rainfed conditions and 90 Mt under irrigated conditions (for comparison, the United States harvested 62 Mt of wheat in 2012, FAO, 2014). The higher uncertainty of the rainfed estimates in Figure IV-4 is caused by the better performance of the crop growth model in simulating potential wheat yields under irrigated conditions (Schierhorn et al. 2014).

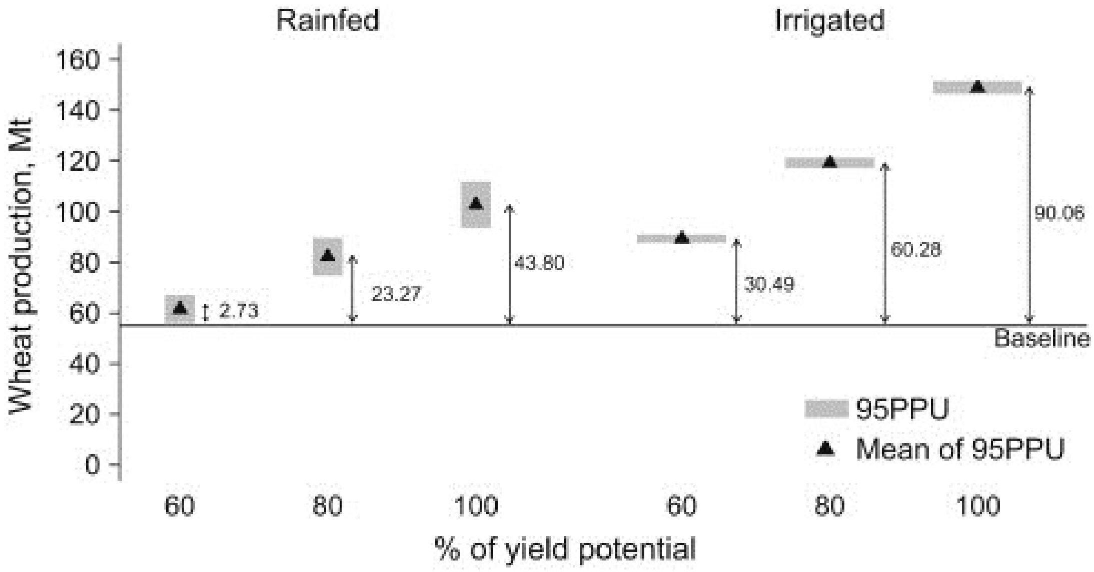

Figure IV-4: Wheat production potentials (million tons, Mt) with different degrees of yield gap closure (60%, 80%, and 100%) on existing croplands under rainfed (left) and irrigated conditions (right). The triangles represent the average potentials of the 95% prediction uncertainty (95PPU) in wheat production between 1995 and 2006, the error bars depict the 95PPU in wheat production potential and the arrows indicate the potential additional production.

Weather conditions — and particularly water availability — during the growing period are crucial for wheat production in rainfed systems in European Russia. The lack of precipitation can severely reduce the crop output, even with an optimal N fertilizer supply, as indicated by the large interannual variation in the wheat production potential for rainfed systems (Figure IV-5). For example, the wheat production potential with a complete yield gap closure under rainfed conditions in 1995 (a severe drought year) was 48 Mt or 38% lower than that in 1997 (a year with good weather conditions).

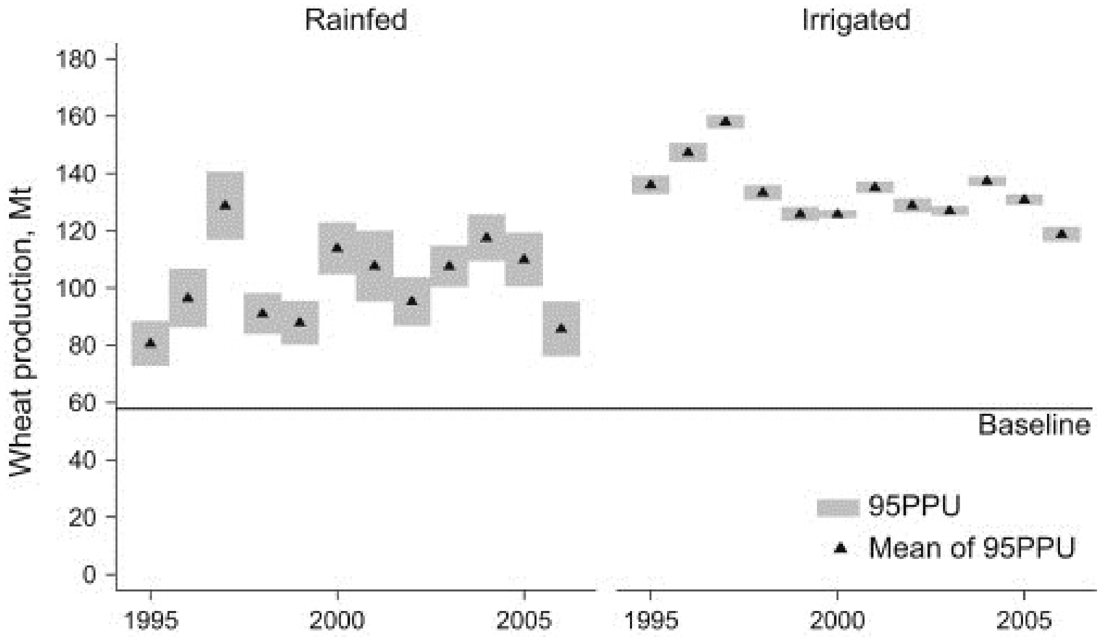

Figure IV-5: Annual wheat production potentials (Mt) with 100% of the yield potential on existing croplands under both rainfed (left) and irrigated conditions (right). The error bars depict the 95% prediction uncertainty (95PPU) in wheat production potential.

The potential wheat production on existing cropland is substantially higher and less variable in years without water stress (Figure IV-4), emphasizing that the expansion of irrigated areas in combination with an optimal N fertilizer supply is a key to increase production and decrease production volatility. While irrigation expansion is unrealistic at a large scale due to water shortages in many locations (Alcamo et al. 2007) and to prohibitive investment costs at the current price ratios of wheat and irrigation technologies, it can alleviate water stress in areas where irrigation water and investment capital are available.

We found the largest wheat production potential on currently cultivated croplands in the fertile black soil belt (Figure IV-6, A) where large sowing areas of grain coexist with large yield gaps (Figure IV-2). The production potentials under rainfed conditions on the existing cropland are lower outside the black soil areas because the sowing areas are smaller. Production potentials are also low in some provinces in southern European Russia where the yield gaps under rainfed conditions are small (for example, Volgograd and Penza, Figure IV-6, A).

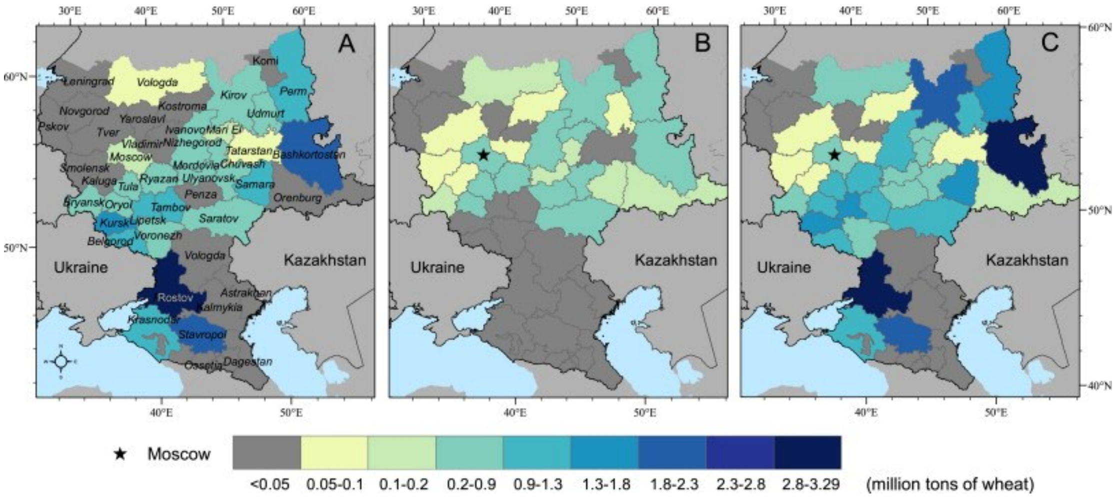

Figure IV-6: Spatial distribution of the wheat production potentials (Mt), with 80% of the yield potential under rainfed conditions on existing cropland (A), from the re-cultivation of the 4.4 Mha of cropland that had been abandoned since 2000 (B), and overall (C).

Production potential of abandoned cropland

Depending on the degree of yield gap closure, the re-cultivation of all of the abandoned croplands with wheat would increase the wheat production between 23 and 40 Mt under rainfed conditions (Figure IV-7, A) and between 23 and 58 Mt under irrigated conditions (Figure IV-7, B), albeit at high carbon emissions and re-cultivation costs. The re-cultivation of the 4.4 Mha with low carbon stocks (see section 0) would increase wheat production by 6 Mt with average actual yields between 1995 and 2006 and by 12 Mt with a full yield gap closure under rainfed conditions (Figure IV-7, A). The spatial distribution of provincial production potentials on the recently abandoned croplands is shown in Figure IV-6 (B). Production increases on the recently abandoned croplands are greatest in temperate European Russia and are lower towards the south.

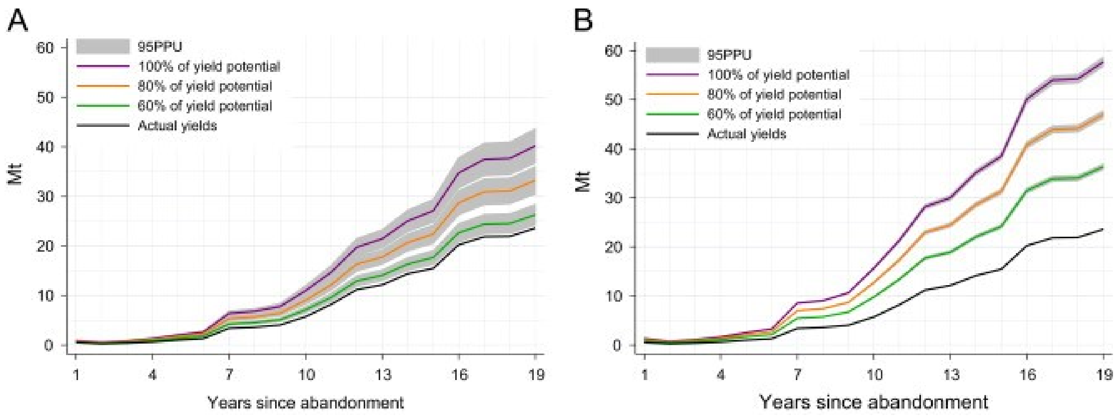

Figure IV-7: Wheat production potentials (Mt) with different degrees of yield gap closure on abandoned cropland under rainfed conditions (A) and irrigated conditions (B). The lines indicate the average potentials of wheat production between 1995 and 2006. The years since abandonment, with 2010 as the reference year, capture the production potential on the cropland that had been abandoned since 1990 (for example, 19 years since abandonment is equivalent to 27.2 Mha of abandoned land). Note that our approach integrates only a share of the abandoned land.

The additional wheat output for the 4.4 Mha is similar under irrigated and rainfed conditions because water stress is lower in temperate European Russia, where the 4.4 Mha are largely located (Figure IV-7, A and B). Moreover, the variation in the wheat potential between 1995 and 2006 under rainfed conditions is less volatile in this region (Figure IV-8, A and B). Therefore, the large production losses due to recurring droughts on the currently cultivated cropland in the southern black soil region may be partially but constantly offset by the re-cultivation of the recently abandoned cropland in temperate European Russia.

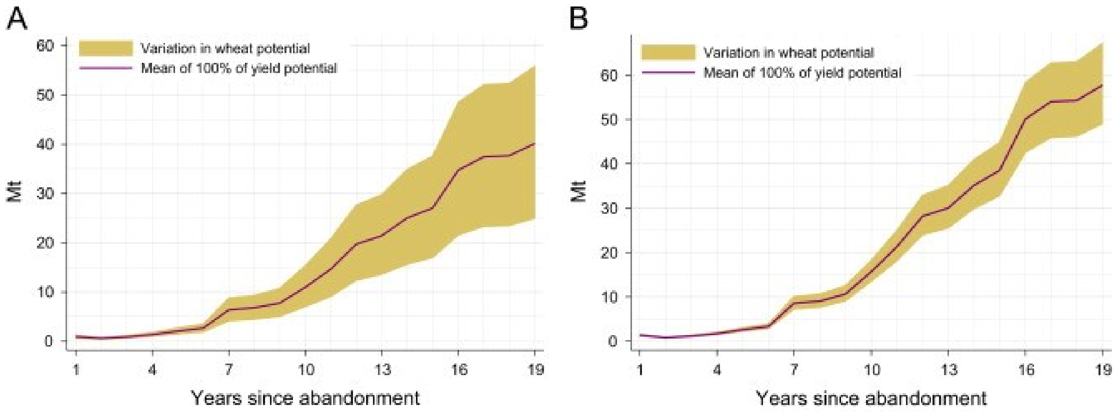

Figure IV-8: Variation in the wheat production potentials (Mt) between 1995 and 2006 with full yield gap closure under rainfed conditions (A) and irrigated conditions (B). See the caption of Figure IV-7 for an explanation.

Overall production potential

The overall wheat production potential comprises production from currently cultivated croplands and the re-cultivation of abandoned croplands under different assumptions of yield gap closure. Most developed countries achieve crop yields of up to 80% of their yield potential (Cassman et al. 2003), and this characteristic may apply to Russia as well. We therefore assumed that the wheat yields on the currently cultivated croplands and on abandoned croplands increase to 60% and to 80% of the yield potential under rainfed conditions. We excluded the simulated yield potentials under irrigated conditions because current cropping systems in European Russia are almost completely rainfed. Re-cultivation was restricted to the 9.5 Mha of recently abandoned cropland, of which only 4.4 Mha are available for wheat re-cultivation in our scenario (see 4.2).

Our assumptions about cropland expansion and yield increase resulted in additional production potentials of wheat in the range of 9 and 32 Mt. Clusters of high wheat potentials are concentrated in southern and northeastern European Russia, where large yield gaps under rainfed conditions co-occur with large areas of unused cropland. The provinces of Stavropol, Rostov, Bashkortostan, and Kirov have the largest untapped production potentials under rainfed conditions for wheat in European Russia (Figure IV-6, C).

Discussion

We demonstrated that European Russian can substantially increase its wheat production and satisfy a substantial share of the projected increase in the wheat demand. Most production increases will likely come from increasing yields on existing croplands and thus entail low carbon emissions from re-cultivation. We advocate higher production potential on the currently cultivated croplands than recent projections for wheat production in Russia (FAPRI-ISU 2012; Liefert et al. 2010; OECD-FAO 2013; Salputra et al. 2013) because we accounted for the large yield gaps. Our projection seems realistic because we assumed only a partial closure of the current yield gaps to 60% and to 80% of the yield potential under the prevailing rainfed conditions. Moreover, we ignored technological progress, which can increase the yield potential by developing improved wheat cultivars (Hall and Richards 2013).

Our yield gap analysis for Russia is based on calibration of the SWAT model under N-limiting conditions using statistical data for actual nitrogen applications and actual yields. We assumed that the calibrated model can be used to simulate potential yield under conditions without N and water limitation. This assumption requires further testing with experimental data, and hence our simulations of yield gaps should be regarded as initial estimates. However, our potential yields are likely to be conservative because we used a conventional wheat variety from the default SWAT database. Current wheat yields in a biophysically comparable region in Central Germany (Magdeburg Börde) average 8 t ha^{-1} (Nehring 2011) and are thus substantially higher than our simulated potential yields under irrigated conditions in European Russia (about 6 t ha-1, Schierhorn et al. 2014). Moreover, the interpolation of monthly weather data to daily data has implications for the quality of yield simulations (van Wart et al. 2013a).

Our scenarios regarding the re-cultivation of idle cropland are conservative because we only included recently abandoned cropland to avoid substantial carbon emissions from re-cultivating croplands that were abandoned soon after the dissolution of the Soviet Union in the early 1990s. Accounting for the carbon trade-offs leaves 4.4 Mha available for re-cultivation, which is lower than previous assessments of the potentially available cropland in Russia (FAO/EBRD 2008; Lambin et al. 2013; USDA-FAS 2008). Wheat production on the 4.4 Mha and with average wheat yields from 1995 to 2006 can increase the production by 6 Mt, which is almost four times less than the production potentials on existing croplands and only 19% of the our estimated maximum production potential of 32 Mt. One reason for this increase is that most of the 4.4 Mha is located north of the black soil areas, where the environmental conditions are only moderately suitable for wheat production. In other words, higher land productivity will be crucial to increase wheat production in Russia, whereas cropland expansion is only of minor importance if the carbon costs resulting from cropland re-cultivation would be accounted for.

Nutrient limitation is an important reason for the large yield gaps in European Russia (Schierhorn et al. 2014). Fertilizer use in Russia is still substantially lower than during the late Soviet Union period in the 1980s (ROSSTAT 2014) and lag far behind that of Western Europe and the United States (FAO 2014). The low input use in Russian grain production most likely indicates structural problems at the farm level, low farm-gate output and high input prices, as well as institutional deficits (Liefert and Liefert 2012; Swinnen and Van Herck 2011). Incentives to invest in more inputs depend, *inter alia*, on transparent and persistent institutions and policies, which might ensure a stable return from crop production. However, the country's institutions are still pending somewhere between a centrally planned and a market-oriented economy (Liefert and Liefert 2012; Swinnen and Van Herck 2011). Other obstacles for the agricultural sector include outdated rural infrastructure, low public and private investments in agricultural research and development, and a considerable lack of qualified farm labourers and managers (FAO 2009; Swinnen and Van Herck 2011). These constraints reduce the profitability and increase the risk of farming and negatively affect the investment behaviour of Russian farms (Bokusheva et al. 2007).

Production risks in Russian agriculture are high for a variety of reasons. First, the volatile climate conditions translate into volatile returns from agriculture in the absence of sound insurance systems to protect against production shortfalls (Bobojonov et al. 2014; Dronin and Kirilenko 2011) and because Soviet-time irrigation systems have largely deteriorated. Irrigated cropland decreased from 2.3 to 0.9 Mha between 1990 and 2006, a decrease of 61% (ROSSTAT 2008). Investments in irrigation, particularly in the black soil belt, may considerably reduce the yield volatility and increase incentives to invest in production. Another promising avenue to stabilize and increase yields is plant breeding, to, for example, introduce drought-tolerant crop cultivars (Araus et al. 2002; Howden et al. 2007; Reynolds et al. 2011).

However, the research and development of plant breeding by Russian research institutes and private companies is scant and the lack of plant cultivars that are adapted to local conditions remains a major bottleneck in crop production (FAO 2009).

Second, wheat production is exposed to considerable price risks because Russian grain producers depend on exports and thus on volatile world market prices. The recent high price volatility in the global grain markets has been amplified by government interventions, such as export restrictions in response to the 2010 drought, which aimed to protect domestic consumers from increasing food prices. These export restrictions caused a disconnection between the domestic and world market prices and incurred high costs for Russian grain producers, forcing them to sell wheat far below the world market price (Götz et al. 2013). Such policy interventions have created an unstable and unpredictable business environment that affects the investment behaviour of farmers and credit lenders (Swinnen and Van Herck 2011). In response, many farmers limit their inputs to avoid the risk of investment losses.

Land expansion on recently abandoned croplands in temperate European Russia can reduce the production shortfalls that are caused by droughts in southern European Russia. However, investments in rural development are imperative to counteract the infrastructural degradation and enormous rural depopulation in temperate European Russia (Ioffe et al. 2004). Such investments are urgent because the environmental and economic costs of re-cultivating idle croplands increase with the time since abandonment, and every additional year of successional vegetation will render re-cultivation more costly in terms of re-cultivation efforts and carbon emissions.

Our time-discriminating approach to evaluate the production potentials for cropland accounts for the carbon emissions that are incurred by land-use change. However, we did not consider other greenhouse gas emissions that are associated with intensifying production, such as emissions of fertilization and higher energy use from producing inputs and mechanization (Matson et al. 1998; Snyder et al. 2009). Moreover, we disregarded institutional and socio-economic factors (for example, land market, labour supply, and accessibility) that may constrain the re-use of abandoned cropland (Deininger et al. 2011; Lambin et al. 2013). Finally, we simulated yield potentials with observed recent weather conditions, but the yield potential will be influenced by future climate conditions. The projected climate change suggests increases in the drought frequency and thus more frequent production shortfalls, particularly in the southern breadbaskets (Alcamo et al. 2007). Initiatives to adapt crop production to climate change are therefore critical and should include both agronomic (for example, irrigation, increasing water productivity, minimum tillage, and rotations) and genotypic (development of drought-tolerant varieties) improvements (Challinor et al. 2014; Faramarzi et al. 2009; Turner and Asseng 2005).

Acknowledgements

This manuscript benefited from the valuable contributions of Friedrich Koch, four anonymous reviewers, and Martin van Ittersum. We are grateful for the financial support of the Leibniz Association's "Pakt für Forschung," the German Federal Ministry of Education and Research (BMBF) (Code01 LL0901A), and the German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV) (GERUKA).

Chapter V Synthesis

Summary and main conclusions

Humanity has the tremendous challenge to substantially increase agricultural output in order to achieve food security. This challenge includes adaptation of agricultural production to climate change, but also to safeguard ecosystem services, biodiversity conservation, and improving livelihood in subsistence agriculture. It is therefore imperative to identify agriculturally underperforming regions, where agricultural production increases entail low environmental and social trade-offs. In this context, the former Soviet Union holds great promise because of vast and fertile land resources that are not utilized to their full potential due to vast amounts of abandoned cropland and large yield gaps. However, the region has been largely underrepresented by the international research community. To date, the extent and spatial pattern of idle agricultural potentials and the environmental costs (e.g., carbon costs) to materialize the potentials were highly uncertain. The goals of this dissertation was first to quantify abandoned croplands, second, to assess the carbon trade-offs of re-cultivating abandonment, third, to simulate the yield gaps, and, fourth, to systematically quantify the untapped agricultural potentials in European Russia. To attain these goals, spatially explicit and process-driven models were used that addressed the following three major research questions:

Research Question I (Dissertation chapter II): What are the spatial and temporal pattern of post-Soviet cropland change and how large are the carbon fluxes due to cropland change?

The detection of large-scale agricultural land abandonment via remote sensing is typically hampered because of the low spectral contrast between active agriculture and early successional vegetation (Alcantara et al. 2013). Moreover, remote sensing products mostly lack detailed information regarding the timing of abandonment, but temporally explicit maps are imperative, for example, to simulate carbon fluxes due to cropland change. Thus, temporally explicit maps allow us to assess the environmental trade-offs inherent in potential re-use of abandoned land (Poeplau et al. 2011). Alternative methodologies for mapping the spatial and temporal pattern and dynamics of cropland abandonment were timely for the Former Soviet Union. Chapter II presents the first wall-to-wall map of cropland change for European Russia, Belarus, and Ukraine at 1 km spatial resolution and an annual temporal resolution from 1991 to 2009. The map is based on a spatial allocation model that distributes yearly and subnational sown area statistics to the areas that are most suitable for agriculture. With this model, reliable cropland maps were produced. Although not systematically validated and without conclusive evidence, our findings suggest that the spatial allocation model was also useful to produce cropland abandonment maps.

The results show that post-Soviet cropland abandonment has often been severely underestimated in previous studies that have mostly relied on agricultural inventory statistics from the FAO. However, FAO fails to capture the large amounts of abandoned cropland. Our new annual cropland maps demonstrated that cropland change after the dissolution of the Soviet Union in 1991 was widespread in European Russia, where 27.3 Mha of former cropland were abandoned between 1990 and 2009. Cropland abandonment was less substantial in Ukraine and Belarus, suggesting limited scope for cropland expansion. Therefore, Ukraine and Belarus were not captured in the Chapter III and Chapter IV of this dissertation. Spatial clusters of abandonment appear in the central northern part as well as in the southern steppe regions at the border with Kazakhstan. Chapter II also revealed that most of cropland abandonment occurred within the first 10 years of the dissolution of the Soviet Union. Re-cultivation has mainly been taking place after 2000 and concentrated in the fertile Chernozem region of European Russia.

The underestimation of cropland abandonment in previous studies also suggested incorrect estimates of the amount of carbon sequestered due to abandonment. We calibrated the dynamic vegetation model LPJmL with the annual cropland maps to better quantify carbon fluxes due to post-Soviet cropland change. The results revealed that a net carbon sink developed after approximately seven to eight years, corresponding to the time required for successional vegetation to establish on the abandoned cropland. This was in line with scattered regional field measurements. A hotspot of carbon accumulation was found in the central northern part of European Russia, where cropland abandonment occurred extensively and early in the 1990s and where climatic conditions facilitated high plant productivity. Total carbon sequestration due to cropland abandonment in European Russia and

Ukraine was 470 TgC for the 1991-2009 period, equivalent to one-third of total US CO_2 emissions in 2012 if released. The annual carbon sequestration rate on the post-Soviet croplands of European Russia, Ukraine and Belarus hence compensates for approximately 4% of the total CO_2 release due to global land-use change. Therefore, the abandoned cropland in European Russia is an important terrestrial carbon sink. Re-cultivating all abandoned areas could not only release a considerable share of the 470 TgC into the atmosphere but would also result in substantial forgone future carbon sequestration because the sequestration rate for mature natural vegetation on these lands would be approximately 50% higher than the current abandoned croplands.

Research Question II (Dissertation chapter III): How large are the yield gaps in wheat production in European Russia?

Global applications of crop growth models as well as statistical approaches have identified large yield gaps for Russia (Balkovič et al. 2014; Licker et al. 2010; Liu et al. 2007; Neumann et al. 2010), but the results are likely tainted with considerable uncertainty, mainly because of coarse or inaccurate input data. Chapter III presents the first regional quantification of yield gaps in wheat production in European Russia. We calibrated a crop growth simulation model with regional agricultural inventory data for annual provincial wheat yields and used the calibrated model to simulate yield potentials under 1) optimal N fertilizer supply in rainfed conditions and 2) optimal N supply in irrigated conditions. Yield gaps, i.e., the difference between potential and actual yields, were quantified for all the provinces with significant sowing area of wheat.

We used the SWAT because of its possibilities for calibration, validation, sensitivity analysis, and uncertainty assessment. We calibrated the SWAT separately for the 28 provinces using the finest available agricultural inventory data to account for the large spatial heterogeneity of the study area regarding the conditions for wheat production. The results revealed that the calibrated models reliably simulated the observed wheat yields and were thus useful to approximate yield potentials.

Average yield gaps were 1.51-2.10 t ha^{-1} (44-52% of potential yield) under rainfed conditions, with considerable variation across space and time. Chapter III further demonstrated that low N fertilizer supply is an important driver for low wheat yields in most provinces. Water stress also contributes to low wheat yields, particularly in the spring and in wheat regions that are characterized by high interannual climatic volatility. Optimal nitrogen supply in combination with irrigation would increase wheat yield by 3.14-3.30 t ha^{-1}. Thus, improved fertilizer and water use are important management strategies to close yield gaps in European Russia. Chapter III helps inform policy makers and agricultural investors to devise measures that target higher yields and reduce yield gaps through input intensification.

Research Question III (Dissertation chapter IV): How large is the potential of European Russia to increase its wheat production?

Chapter IV of this dissertation assessed the potential production of wheat in European Russia by combining the results of the previous two chapters. Assumptions about cropland expansion at the expanse of the area of abandoned cropland (Chapter II) and yield gap closure on cultivated cropland (Chapter III) resulted in estimates of additional production potentials of wheat. Chapter IV shows that European Russia can substantially increase its wheat production (up to 32 Mt under rainfed conditions). Although higher than recent projections for wheat production in Russia, our results are likely still conservative because we assumed that the expansion of wheat cultivation commences on the recently abandoned cropland to reduce the trade-offs from the high carbon emissions in re-cultivating older abandoned cropland. In addition, we assumed only a partial closure of the yield gaps, excluded the expansion of irrigated areas, and ignored technological progress, all of which can increase the yield potential.

The wheat production potential from cropland expansion are relatively small if the high carbon costs resulting from re-cultivation are accounted for. We advocate limited re-cultivation of abandoned land because greenhouse gas emissions for producing crops on abandoned land occur as a result of converting successional vegetation to cropland and during crop cultivation and harvesting (for example, for fertilization and machinery). However, the results also demonstrate that land expansion in temperate European Russia, where substantial cropland abandonment also occurred recently (after 2000) and thus only small amounts of carbon were sequestered, will reduce recurring production shortfalls that are caused by droughts in southern European Russia.

Most production increases will likely result from increasing yields on existing croplands. Most importantly, Russian farmers should find strategies to overcome large gaps in the supply of nitrogen fertilizer. However, recurring climate-driven production shortfalls are another major obstacle for agricultural production in Russia. The southern Chernozem regions, where crop production is concentrated, are already burdened by volatile climate and climate change is expected to increase the frequency of summer droughts and heat stress in this region. Chapter IV demonstrated that stable increases in wheat production in this region can only be attained if plant water stress is alleviated in the southern breadbaskets of European Russia. Therefore, investments in drought-resistant crop varieties and promotion of agronomic practices that are adapted to the volatile climate conditions, such as crop rotations, minimum tillage, and sustainable water use for irrigation, are imperative to help increasing long-term crop productivity. Policies in Russia should create the proper framework that Russian farmers will have better financial and infrastructural conditions to put adaptation to the volatile climate and climate change into practice. Policies in Russia should also aim at to reduce investment risks for agricultural inputs, for example, through improved agricultural insurance programs that help levelling out production shortfalls.

Future research

The former Soviet Union countries are already targeted by domestic and foreign land investors (Visser and Spoor 2011). However, rapidly increasing food demand and the looming scarcity of suitable agricultural land on the one side and widespread idle agricultural land and low land prices in the eastern breadbaskets on the other suggest that transnational land acquisitions will increase both in number and area extent. Moreover, not just since the recent political crisis and the Russian import ban on agricultural products, the Russian government aims for higher degree in self-sufficiency in livestock production, suggesting a looming domestic rush for idle agricultural land (Wegren 2011). Therefore, it is imperative to identify regions in the FSU where agricultural land expansion, particularly to abandoned land, will make relatively small environmental and socio-economic footprints.

In this dissertation, the carbon sequestered due to cropland abandonment was simulated for each grid cell to limit the carbon costs due to re-cultivation. However, social, economic and environmental trade-offs other than carbon are also associated with land re-cultivation but were beyond the scope of this work. Further research may assess the biodiversity conservation value of abandoned agricultural land to better balance biodiversity conservation and food production (Plieninger et al. 2014; Queiroz et al. 2014). Moreover, follow-up research is also imperative to gain a better understanding regarding claims of land property rights as apparently idle land may already be in property and used, for example, by smallholders or livestock herders. Future research should also focus on the economic costs inherent in re-cultivation of abandonment land for the benefit of policy makers as well as domestic and foreign agricultural investors.

Teleconnections and the displacement of land use add more complexity to the question of whether abandoned land should be reused, particularly in the case of Russia (Schierhorn et al. in preparation). The livestock sector in Russia collapsed after 1991, and Russia subsequently became one of the largest net importers of meat and milk, particularly from South America and Europe (FAO 2014). Therefore, environmental costs in terms of carbon emissions and loss of biodiversity due to tropical deforestation, were embodied in the trade of livestock products to Russia (Caro et al. 2014; Karstensen et al. 2013). When factoring in the embodied environmental costs of trade, the footprint of land re-cultivation in Russia changes drastically. For example, land use change in the tropics typically comes at much higher carbon cost than in temperate regions, mainly because tropical forest biomes store the highest amounts of carbon in the biomass (Ruesch and Gibbs 2008). Comprehensive studies should account for such distant drivers. For example, an assessment of the potential of Russia to increase its self-sufficiency in livestock products would reveal interesting insights that could serve to quantify potential reduction of environmental pressure elsewhere.

This dissertation presents the first regional quantification of yield gaps in wheat production in European Russia. However, the environmental and economic trade-offs inherent in strategies to close yield gaps were beyond the scope of this dissertation. It would be interesting to assess the greenhouse gas emissions associated with higher inputs and different agronomic practices (for example, fertilization, tilling, machinery use, irrigation, etc.) to close yield gaps (Cui et al.

2013; van Noordwijk and Brussaard 2014). Moreover, the availability of sustainable water resources for irrigation in the current conditions, the impact of climate change, and the development of drought-tolerant crop cultivars remain important avenues for future research. This dissertation revealed that the utilized crop growth model is well suited for such applications, but future applications should integrate experimental data from field measurements for a more nuanced model calibration and validation. Moreover, the use of model ensembles in crop modelling is imperative to generate robust assessments of climate change impact studies (Asseng et al. 2013), and would help advancing the understanding of production potentials for this globally important breadbasket region.

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Eidesstattliche Erklärung

Hiermit erkläre ich, die vorliegende Dissertation selbstständig und ohne Verwendung unerlaubter Hilfe angefertigt zu haben. Die aus fremden Quellen direkt oder indirekt übernommenen Inhalte sind als solche kenntlich gemacht. Die Dissertation wird erstmalig und nur an der Humboldt Universität zu Berlin eingereicht. Weiterhin erkläre ich, nicht bereits einen Doktortitel im Fach Geographie zu besitzen. Die dem Verfahren zu Grunde liegende Promotionsordnung ist mir bekannt.

Florian Schierhorn

Halle, den 03.02.2015